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20 August 1979

USSR Report

ENGINEERING AND EQUIPMENT

(FOUO 3/79)



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USSR REPORT
ENGINEERING AND EQUIPMENT
(FOUO 3/79)

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ENGINEERING AND EQUIPMENT

UDC 621.375.8+533.9:621.039.61

ON THE PROSPECTS FOR CONSTRUCTING A LASER THERMONUCLEAR POWER PLANT

Moscow ENERGETIKA I TRANSPORT in Russian No 2, 1979 pp 3-8

[Article by N. G. Basov, O. H. Krokhin, V. B. Rozanov, A. Ye. Sheyndlin, R. R. Grigor'yants, A. V. Kalinin and E. E. Shpil'rayn]

[Text] The most important aspects of the conceptual design of a "clean" laser thermonuclear power plant are examined in this article. The physical prerequisites of the development of LTES and the basic engineering decisions, made during the course of planning, are discussed. A comparative analysis is presented and the choice of reactor design and energy converter system is substantiated. The basic characteristics of LTES and some technical-economic estimates are presented.

In the state of the art of laser thermonuclear fusion there are, conditionally, of course, four groups of problems:

- 1) problems of the laser system;
- 2) problems of the target;
- 3) problems of the reactor;
- 4) problems of converting the energy from thermonuclear microexplosions and laser thermonuclear power engineering as a whole.

A comprehensive project, undertaken jointly by the Physics Institute of the USSR Academy of Sciences and the High-Temperature Institute of the USSR Academy of Sciences, was supposed to show how a laser thermonuclear power plant [LTES] -- a laser thermonuclear generating station -- might look at the level of knowledge and technology available to us today and in the coming decade.

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A laser-driven thermonuclear reaction can be imagined schematically as follows: a deuterium-tritium microtarget (a ball about 1 mm in diameter), placed at the focus of a multichannel laser system, is subjected to spherically symmetric irradiation by a nanosecond or sub-nanosecond laser pulse. The energy flux density on the surface of the target reaches 10^{12} - 10^{15} W/cm². The outer layer of the target is vaporized, forming a plasma corona that explodes outward at a velocity of about 10^8 cm/s, and a compression wave spreads through the target. Building up at the center, this wave produces a clot of superdense hot plasma (with a temperature of about 10 keV and a density of 10^{25} - 10^{26} cm⁻³), and this is where the thermonuclear reaction begins. The wave of the thermonuclear reaction, spreading from the center of the exploding plasma ball and gradually weakening, engulfs much of the material of the target -- the depth of burnout reaches 10% before free escape causes the plasma to cool. The energy released eventually exceeds the energy of the laser pulse. Thus, laser thermonuclear synthesis is something like a microexplosion. Estimates indicate that a target with a diameter of 100 μ produces a microexplosion equivalent to ~5 kg of TNT. Although the time of free escape (inertial confinement) of the laser plasma is $\sim 10^{-10}$ s, its high density yields $n\tau \sim 10^{15}$ - 10^{16} , satisfying Lawson's condition, which corresponds to a 100-fold amplification of energy.

A specific and, apparently, not the most widely accepted feature of the DT-reaction is the fact that most of the energy released (14.1 of 17.6 MeV per explosion) is carried off by fast neutrons with a high penetrating capacity, and charged particles account for only about 23%. The effective conversion of the energy of thermonuclear microexplosion products -- fast neutrons and alpha particles -- to one of the forms of energy dictated by the structure of consumption (electricity, heat, chemical or nuclear energy of secondary fuel), poses a difficult scientific-engineering task. A thermonuclear microexplosion, generating monoenergetic streams of particles, represents, in principle, a unique source of low-entropy energy. However, it is extremely difficult to find adequate schemes for the conversion of this energy, based on the technological capabilities of today, or even of the foreseeable future.

As for a laser system, briefly, the ideal laser system for LTS [laser thermonuclear synthesis], must obviously meet the following requirements:

wavelength	0.5 μ
beam energy (per pulse)	10^6 J
energy release density (per unit volume of active sphere)	0.5-1.0 J/cm ³
efficiency of laser system	10%
pulse duration	(0.1-1.0) ns with optimum profiling capability
repetition frequency	1-100 Hz
number of pulses	more than 10^8

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Not a single one of the existing laser systems completely satisfies these requirements.

The instrument that is best developed in the design and technological aspects is the solid state neodymium glass laser, used up until now in most experiments on the laser irradiation of targets. The deficiency of this laser is its low efficiency (0.2-0.3%), chiefly due to the ineffectiveness of its photopump. Selective pumping methods elevate the efficiency of the Nd-laser to 1-2%, but even in this case the benefit of using an Nd-laser in the laser thermonuclear power plants is doubtful due to the high cost and low tolerable temperature of neodymium glass as an active medium.

The CO₂-laser is considered to be an extremely promising laser for LTS, especially after it was shown that the relatively long wavelength of the main line (10.6 μ /mm) does not impede the effective absorption of laser energy in plasma. Improvement of the pumping system, especially the use of short-pulse electron beams, can be expected to increase efficiency to 15-20%. Along with providing an opportunity for the effective utilization of the heat dissipated by the CO₂-laser, this will make the CO₂-laser an extremely likely candidate for laser thermonuclear power plants.

The chemical HF-laser, which is essentially a device that directly converts chemical energy to the energy of coherent radiation, is another promising type of laser. The apparent efficiency of an HF-laser with an electron pump ranges up to 300%, but in consideration of the cost of regenerating the working medium it is 2-3%. Improvement of regeneration technology will elevate the efficiency of the HF-laser to 4-6%, which can make it a favorite candidate for LTS energy applications.

As the result of a comparative analysis the CO₂-laser system with a presumed pulse energy of $5 \cdot 10^5$ J and 5% efficiency was chosen for the power plant project.

Let us now discuss a laser thermonuclear reactor (LTR). Such a reactor should provide the following:

the optimum conditions for insertion of the DT-target and injection of the laser radiation;

confinement of the combustion products within the intact shell -- explosion chamber -- and the first step of conversion of the energy of the thermonuclear microexplosion;

capability for repeating microexplosions many times in the quasicontinuous mode at a high enough frequency;

capability for the reproduction of tritium.

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Many conceptions of the explosion chamber (EC) are discussed in the literature. The most interesting of them are considered to be EC with a "wet" wall, EC with a dry wall, EC with a magnetic wall and EC with a liquid wall.

In the "wet wall" system the problem of the first wall of the microexplosion thermonuclear reactor is solved by using a film of liquid metal on the first wall. The first wall in this case may be, for example, a laminated screen, the porosity and thickness of which are selected such as to guarantee the absorption of α -particles and γ -rays of the microexplosion in a thin film, for example lithium, which coats the inner surface of the explosion chamber. The film is replenished in the multiple microexplosion mode from an external lithium source -- a blanket, the main functions of which are to slow down and absorb fast neutrons and to reproduce lithium.

The ideal "dry wall" chamber is never rejuvenated during the course of the run for which it is designed. A high-boiling substance, for example graphite, vaporized from the wall by fluxes of α -particles and γ -rays, precipitates in a short time due to intensive external cooling. Of course, the shape of the cavity is strongly distorted in time, but according to estimates, the time in which catastrophic changes of the shape of the cavity occur can be made long enough so that this solution could be considered to be technically important.

A magnetically controlled (or with a magnetic shield) LTR system offers potentially great possibilities. As before, of course, we refer to thermonuclear systems with inertial confinement. A comparatively weak magnetic field (10-20 kGs), which has virtually no influence on the compression and thermonuclear combustion processes and the initial stage of the escape of DT-plasma, is used in such systems for protecting the first wall of LTR from direct fluxes of α -particles. The controlling magnetic field can, in principle, be organized in such a way that MHD-conversion of the energy of the microexplosion plasma and of the residual gas to electricity (an induction MHD-generator using thermonuclear microexplosion products) will take place in the LTR explosion chamber. Calculations done at IVTAN have shown that up to 90% of the kinetic energy of α -particles can be converted and supplied to an external active load in a time of $\sim 10^{-5}$ s with an initial field of 10 kGs. The utilization of an electromagnetically controlled LTR for the fastest possible evacuation of thermonuclear microexplosion products from the explosion chamber for the purpose of increasing the possible microexplosion repetition frequency, and thus the thermal power of the reactor, offers another interesting possibility.

Schemes of LTR with moving walls, one of which (the "Blascon" scheme [1]) has been the subject of discussion in the literature for quite a long time, seem exceedingly exotic. In this case a rotating funnel in liquid lithium, flowing from the explosion chamber through a drain in the floor, is used for making a microexplosion.

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IVTAN has suggested and examined another LTR plan with moving walls: a thermonuclear microexplosion is supposed to take place in a lithium cavern, formed beforehand by injecting lithium vapor electromagnetically or ultrasonically. Minimization of the amount of activated construction materials in the zone of strong neutron fluxes is an indisputable advantage of LTR with moving walls, and these systems are closest to the ideal "point explosion in an inorganic (lithium) hydrosphere" model, which evidently yields the theoretically maximum tritium reproduction coefficient of 1.58. However, not one of these plans has yet found completely reliable experimental or even theoretical confirmation.

An analysis of various conceptions of LTR, completed jointly by IVTAN and FIAN [Physics Institute imeni P. N. Lebedev of the USSR Academy of Sciences], led to the conviction that the wet wall plan, used earlier in the Los Alamos project and "Saturn" project [2, 3], is soundest for the near future. This LTR plan, with certain modifications, was also used as the basis for the joint FIAN-IVTAN development of a laser thermonuclear power plant. The basic characteristics of the reactor are presented below:

type of explosion chamber	spherical cavity with wet porous wall;
inside radius	5 m;
type of blanket	homogeneous liquid lithium with natural isotope concentration;
thickness of blanket	0.6 m;
lithium temperature at discharge from blanket	700°C;
lithium pressure in blanket	0.2 MPa;
lithium flow rate	390 kg/s;
reactor construction materials	nickel-free stainless steel for elements in contact with liquid lithium (300 t); chromium-nickel stainless steel for elements not in contact with liquid lithium (240 t);
technological shield of reactor	graphite reflector, laminated absorber made of boron carbide (160 t) and lead (425 t);
residual gas pressure in explosion chamber before insertion of target	133 Pa;
method of evacuating explosion chamber	free flow into mixing condenser-heat exchanger;
microexplosion repetition frequency	10 Hz

The inside diameter of the explosion chamber of LTR is determined after a comparative analysis of several factors:

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1. The neutron flux density on the first wall of LTR and on the optical output elements of the laser system.
2. The mass of vaporized material and the time it takes to empty the explosion chamber.
3. The intensity of the shock wave generated in the blanket.
4. The relative concentration of construction materials in the tritium reproduction zone.

An analysis of the calculations disclosed that for chambers with small diameters (~1 m) the proportion of construction materials in the tritium reproduction zone increases prohibitively, which leads to a sharp reduction of the tritium reproduction coefficient. At the same time the neutron flux densities on the first wall reach high levels, $\sim 10^{15} \text{ cm}^{-2}\text{s}^{-1}$, which corresponds to an extremely fast accumulation of the critical neutron dose.

Designing the first wall of LTR in the form of a laminated screen, capable of surviving many cases of structural damage, and increasing the inside diameter of the chamber by an order of magnitude will make it possible to increase the calculated service life of the first wall to the maximum, technically reasonable limit. Sectioning the LTR in the vertical plane and designing into the plan the capability of quickly replacing the entire LTR will make it possible to design a sufficiently reliable LTR in comparison with other elements of a laser thermonuclear power plant, but problems of neutron damage to the construction and optical elements remain extremely critical.

An analysis of the principles of how wave processes take place in the explosion chamber after the target is exploded revealed that the chamber evacuation time gets shorter as the radius of the chamber increases for a fixed ratio between the area of the discharge port and the area of the chamber. A large-diameter chamber also appears to be preferable from this standpoint as well. However, as EC dimensions increase capital investments in the construction of the reactor become more and more burdensome in comparison with the total cost. Therefore a very large chamber, such as the one in the "Saturn" project, is also unacceptable. A chamber with an inside diameter of 10 m, the discharge port of which has a relative area of 5%, was used in the final version.

A CO_2 -laser with an electron pump, a beam energy per pulse of $5 \times 10^5 \text{ J}$ and an efficiency of 5% was chosen as the initiating laser system. Computer experiments indicate that the use of a laser system on the 10^5 - 10^6 J per pulse scale offers hope of achieving an energy amplification coefficient per microexplosion of up to 100 when sufficiently simple targets are used.

However, an extremely high consumption of qualified energy for internal needs should be regarded as a specific feature of laser-driven thermonuclear

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power plants. For instance, the internal needs of a laser thermonuclear power plant (LTES) with a laser efficiency of 5%, LTR amplification coefficient of 100 and energy converter efficiency of 0.4, are equal to the net electricity delivered to the consumer. Such great internal need, exceeding the analogous index of modern thermoelectric power plants by an order of magnitude, undoubtedly will seriously detract from the comparative technical-economic indices of LTES. Therefore the problem of the utilization of the heat dissipated by the laser system is an extremely acute one for LTES. Our plan incorporates a high degree of utilization (theoretically complete) of laser heat. The LTES plan calls for the utilization of laser heat in the first stage of the steam generator-heat exchanger for heating water from 543 to 622 K -- a unique laser economizer, if the steam generator-heat exchanger is viewed as the analog of the boiler of an ordinary steam turbine power plant. The utilization of laser heat will substantially improve the energy efficiency and technical-economic indices of LTES.

The laser thermonuclear power plant developed by FIAN and IVTAN is essentially an attempt to combine a completely nontraditional heat source in the form of the above-described laser thermonuclear reactor and a standard K-300/240 steam turbine unit, series-produced by the industry. The choice of steam turbine unit was determined by the one reactor per turbine principle, which may easily be rejected in future developments, and by the thermal power of the reactor. The "lithium-water" steam generator-heat exchanger with an economizer stage, which utilizes laser heat, is the connecting link in the thermal plan.

Although a laser thermonuclear reactor is by nature a high-temperature heat source, an energy converter with a comparatively low-temperature steam turbine cycle was intentionally chosen in our plan in order to limit the amount of nonstandard equipment and, accordingly, the number of elements of uncertainty in the planned system.

The moderate temperature of the heat transfer agent in the first loop (700°C), corresponding to the top temperature of the working medium of the steam turbine cycle (565°C) enables us to examine the materials analysis problems of the first loop with optimism.

The basic indices of LTES are presented below:

energy release per microexplosion	$5.0 \cdot 10^7$ J
thermal power of energy unit/thermal power of synthesis	620 MW/500 MW
electrical power of energy unit	300 MW
electrical power (net)	170 MW
electrical efficiency of energy unit (net)	0.33

Thus the developed laser thermonuclear power plant has a net electrical efficiency comparable with modern AES with thermal neutron fission reactors.

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Technical-economic analyses indicate that the cost of electricity per installed kilowatt at the LTES depends most substantially on capital investments in the laser system and evidently is double the corresponding indices of series AES, but is on the same cost level per installed kilowatt as power plants with fast neutron breeder reactors.

As for the breeding of fuel LTES has unquestionable advantages, which we feel are appropriate to discuss by way of conclusion.

An LTR with a thermal power of 620 MW and a tritium reproduction coefficient of 1.25, burning 77 g of tritium per day, has a doubling time of about 40 days for an initial charge sufficient for 10 days. The lithium contains about 850 g of tritium with an activity of about 6×10^6 Ci when the plant reaches the stationary tritium concentration. These figures justify optimism in relation to the prospects of "clean" LTES in comparison with other types of nuclear power plants, although the first stage of the adoption of thermonuclear power plants in power engineering obviously will involve so-called hybrid installations, in which a thermonuclear reactor will generate fast neutrons for a heat-generating subcritical uranium assembly.

Conclusions. 1. The design of "clean" laser thermonuclear power plants places extremely rigid requirements on the laser system and fuel target (the energy of induced microexplosions is ≥ 500 kJ, pulse power is ≥ 500 TW, the efficiency of the laser system is $\geq 3\%$, and the thermonuclear energy amplification is ≥ 100 , etc.). However, engineering problems that will arise, as is indicated by the good agreement between the characteristics of the described conceptual design and the characteristics of foreign counterparts, can be solved successfully, even at the level of contemporary technology.

2. The cost of electricity per installed kilowatt of the described kind of LTES should evidently exceed the corresponding index of modern series thermal neutron AES by a factor of 2.0-2.5. Nevertheless, electricity from LTES may become commercially attractive after the cost of uranium increases by about 50-100%, or after the cost of fossil fuel increases by 25-50%, if it is assumed that the fuel component of the calculated cost of electricity for thermonuclear power plants is close to zero, and capital investments in the basic equipment are conservative enough.

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2. Booth, L., et al, "Central Station Power Generation by Laser Driven Fusion," Los Alamos Scientific Laboratory, Report LA-4858-MS, Vol. 1, February 1972.

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3. "Pulsed Fusion Reactor," Trans. Int. School of Fusion Reactor Technology, Frice-Tapany (Sicily), 1974.

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HIGH-ENERGY DEVICES, OPTICS AND PHOTOGRAPHY

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PROBLEMS OF BUILDING LASER DEVICES TO OBTAIN HIGH-TEMPERATURE PLASMA

Leningrad OPTIKO-MEKHANICHESKAYA PROMYSHLENNOST' in Russian No 1, 1979
pp 5-9

[Article by doctor of sciences A. A. Mak]

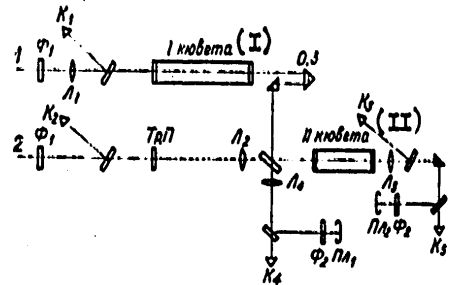
[Text] Research being done in many laboratories of the world [1-4] on laser heating of plasma and the conditions of occurrence of thermonuclear reactions are in large part a result of advances made in the development of powerful lasers and systems based on them. The specific and very complex requirements for characteristics of these lasers make the problem of building them one of the most difficult challenges of laser engineering and optics. In work on this we encounter the necessity of developing complete active laser media and optical materials which are minimally subject to the effects associated with the self-stress of powerful laser beams; methods of obtaining super-short pulses with exceptionally high brightness of brightness; complete optical systems for concentrating with high dimensionality a laser emission with low volume; optical methods of diagnosis with high time (to 10^{-12} - 10^{-13} seconds) and space (microns and fractions of microns) resolutions; problems of automating the alignment, guidance, and control of a complex, multichannel optical assembly containing hundreds and thousands of components. This short list of just a few problems shows how complex and multifaceted the problem under consideration is. Its solution is linked to progress not just in the field of laser engineering proper, but also many key areas of optics and optical technology.

Despite significant advances in the development of lasers on carbon dioxide gas, excimer lasers, and others, one of the primary types of lasers for conducting experiments to obtain high-temperature solid plasma now and in the near future is the neodymium glass laser. Its record values for power output (10^{12} watts) and brightness of emission (10^{18} watts per square centimeter), convenient spectral range of emission, and developed technology give this kind of laser a leading position and many science centers are working on the problems of building them.

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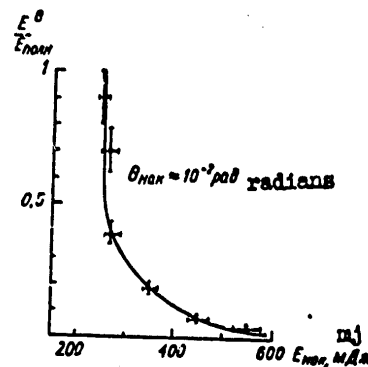
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Figure 3. Chart of an Experiment To Correct a Wave Front of Emission by the Averaging Technique with Forced Combined Scattering in Oxygen: 1 — Channel for Receiving a Start-Up Single-Mode Stokes Signal, $W = 0.1-10$ Mega-joules, $\lambda \approx 0.6$ Microns, $t = 1$ Nanosecond, $\phi = 5 \cdot 10^{-4}$ Radians; 2 — Conversion Channel; Pumping — Emission with An Energy of 0.1-1 Joules, Length of 1 Nanosecond, $\lambda = 0.53$ Microns;



Cell I has a length of two meters and a gas pressure of 20 atmospheres; Cell II has length of one meter and a pressure of 20 atmospheres. $Tp. \Pi$ — Etched Glass Plate that Insures Divergence of Pumping Emission of About 10^2 Rad.; ϕ_1, ϕ_2 — Light Filters; $\Pi_1 - \Pi_4$ Are Lenses; K_1-K_5 are Calorimeters; Π_1, Π_2 Are Cameras; 0.3 is an optical delay line.

Figure 4. Dependence of the Amplified Energy of A Stokes Single-Mode Signal on Pumping Energy.



same time, it does give some idea of the problems and difficulties being met by those who are developing extremely powerful lasers and suggests ways to solve them.

FOOTNOTES

1. Basov, N. G., and Krokhin, O. N. ZhETF 1964, Vol 46, p 171.
2. Prokhorov, A. M., Anisimov, S. I., and Pashinin, P. P. UFN 1976, Vol 119, p 401.

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Work to build lasers to obtain high-temperature plasma was begun in the 1960's at the initiative of academician A. A. Lebedev. Work [5] gives a survey of research done in the 1960's and early 1970's under the direction of M. P. Vanyukov. In the time since this survey was written, research on the problem of laser thermonuclear synthesis (LTS) has received a number of stimulating inputs, the most impressive being the idea of adiabatic compression [4]. This suggestion and analysis of the possibilities of the so-called hybrid cycles led to a situation where the LTS problem began to appear entirely soluble in the near future [2, 4]. The basis for these hopes was the abrupt lowering of requirements for the energy parameters of the laser with a simultaneous increase in the rigor of the requirements for the time and space characteristics of emission and the growing complexity of targets. It was established that the beam energy necessary for ignition may be cut to hundreds and thousands of Joules if the time profile of the pulse of emission is programmed appropriately. Specifically, for a solid target the optimal shape of the pulse is determined by the relation

$$P = \frac{P_0}{\left(1 + \frac{t}{\tau}\right)^2},$$

where $\tau = 10^{-10}$ seconds. With this profile 50 percent of the energy of emission is confined to the time interval 10^{-8} seconds and the other 50 percent lies in the interval 10^{-10} seconds. With such short and powerful pulses the problem of attaining high brightness of emission and laser efficiency became especially critical primarily because of the possibility of self-focusing of the radiation.

In this article an attempt is made to present briefly the most significant results obtained by us in recent years in the field of building lasers for high-temperature warming of plasma.

Obtaining Pulses That Are Profiled in Time

The difficulty of this problem is the result of two factors: the sub-nanosecond length of the pulses, for which there is essentially no equipment to control electrical signals, and the extraordinarily great changes in intensity of emission, 5-6 orders.

An original solution was proposed and accomplished in works [6, 8]. The idea (represented in Figure 1 below) consists of the following. By means of electro-optical deflector device 1 the time coordinate of a Π -shaped pulse of emission is converted to a spatial one. Then the emission passes through optical filter 3 with an assigned variable pass distribution on the X axis and finally, by means of deflector 5, the spatial coordinate is converted back to a time coordinate. In this

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Key: (1, 5) Electro-Optical Deflectors;
 (2, 4) Objectives;
 (3,) Filter with Variable Gating on the X Axis.

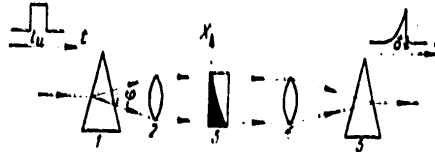


Figure 1. Schematic Diagram ..
 of Profiling a
 Laser Pulse.

way, manipulation of the temporal movement of the emission is replaced by control of its distribution in space. Deflectors 1 and 5 which turn the beam are in the focal planes of objectives 2 and 4, as is filter 3 with variable gating by cross-section. The deflectors are made of KDR [expansion unknown] crystals and when they are thermostated at a temperature close to the Curie point, they can deflect the beam at an angle of about 10^{-2} radians for about 10^{-8} seconds. The actual profiling scheme, of course, is more complex than the one shown in Figure 1 [7, 8]. The degree of accentuation of light pulses achieved δt is determined by the identity of the elements of the evolution and convolution circuits and by the relation of the angular divergence of emission α and the angular velocity of evolution:

$$\delta t = t_u \frac{\alpha}{\phi},$$

where ϕ is the angle of deflection of the radiation. Where $\alpha \approx 10^{-4}$ radians, $\phi \approx 10^{-2}$ radians, $t \approx 10^{-9}$ with $\delta t \approx 10^{-11}$ seconds. Thus, using the proposed method it is possible to obtain accentuation up to 10^{-11} – 10^{-10} seconds. The feasible drop in intensity is about three orders. A subsequent increase in the drop to 5–6 orders and simultaneous correction of distortions of the shape of the pulse which occur during the signal's passage through the amplification line are accomplished by controlled electro-optical gates placed between the amplification series. Analysis of the effect of possible disturbing factors on the shape of the profile of the emission pulse, above all instability of operation of the amplifiers and other elements of the circuits, showed that the proposed scheme is quite stable against disturbances and provides good restoration of the chosen form of the pulse in a setting of the very considerable instabilities that occur in multiseries systems [7].

Self-Focusing of Emission in the Amplification Line and Methods of Controlling It

This problem is one of the fundamental problems in building powerful solid-state lasers for the sub-nanosecond range. Fundamental

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characteristics of a laser system such as efficiency, angular divergence of emission, and reliability depend significantly on solving it.

Suppressing large-scale self-focusing is not a difficult problem in a technical sense; it is adequate for the amplification series to work in diverging (about one degree) beams as proposed in 1968 by A. A. Poplavskiy (see also [9-11]). Their basic difficulties arise with so-called small-scale self-focusing. The emission outputs in use (10^{11} - 10^{14} watts) greatly exceed the threshold output of self-focusing (about 10^6 watts). At the same time, because of the instability of high-intensity laser beams in relation to disturbances of the wave front of emission occurring, for example, with diffraction of the beam at apertures, irregularities, and inclusions in the glass, it is possible for the beam to be broken into a number of individual threads and for them to "collapse" because of self-focusing [1] (a study of the processes of self-focusing in confined beams was made in [13]). This results in the formation of tracks of disintegration and, particularly important, leakage of emission in the distant zone; in other words, a significant part of the emission in the distant zone is pumped into the "wings" corresponding to divergence of 10^{-3} - 10^{-2} radians, as can be seen, for example, in curve six in Figure 2 below. Such effects limit the intensity

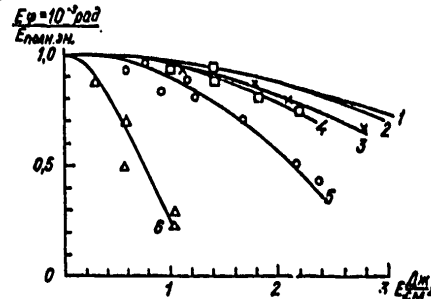


Figure 2. Dependence of the Ratio of the Energy of Emission Confined in the Angle 10^{-3} Radians to Full Energy of Emission at the Amplifier Output on the Intensity of Emission at the Input for Phosphate (1, 3) and Silicate (2, 6) Glasses of Different Composition: 1 — KGSS1621, 1 = 260 mm; 2 — GLS1, 1 = 260 mm; 3 — KGSS1621, 1 = 260 mm; 4 — GLS1, 1 = 260 mm; 5 — GLS1, 1 = 630 mm; 6 — GLS1, 1 = 630 mm. 3, 4, and 6 do not have spatial filtration; 1, 2, and 5 have spatial filtration before the amplifier. The angular dimension of the diaphragm is $6 \cdot 10^{-4}$ radians (curves 1 and 2) and 10^{-3} radians (curve 5).

of emission at the laser output to about 10^9 watts per square centimeter; in other words, where $t_m \approx 10^{-10}$ seconds the permissible energy density is about 0.1 Joules per square centimeter. At the same time, the density of the energy of saturation for amplifiers on neodymium glass, where the reserve energy of excitation is used efficiently, is 5-8 Joules per square centimeter [14]. Thus, the effects of self-focusing do not permit realization of the energy stored in an active medium and reduce the efficiency of the system accordingly.

Work [15] studied the relationship of the nonlinear index of refraction n_2 , which is responsible for self-focusing, on the composition of the

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glass. The characteristics of amplifiers using neodymium glass of various compositions were investigated. As a result, compositions of neodymium glasses for lasers of this type were selected. The results of work to create athermal neodymium glasses in which thermal distortions arising during optical pumping are minimal were also considered here [16-24].

Considerable attention has been devoted to studying amplifiers with active elements of various configurations, in particular discs [25-27]. The efficient pumping systems and techniques for suppression of superluminescence and parasite modes developed made it possible to raise the efficiency and amplification factor of disc amplifiers to values characteristic of core amplifiers.

One of the methods of controlling small-scale self-focusing is the use of diaphragms with diffuse boundaries ("soft" diaphragms). This can markedly reduce disturbances of the wave front of the beam resulting from diffraction at the aperture. "Soft" diaphragms constructed on the basis of different principles have been proposed and studied. "Spatial filters" — a telescope with a diaphragm in its focal plane, are used to restrict the development of self-focusing caused by random disturbances. Placing the spatial filter between amplification series restricts the development of the "wings" of the distant field, making it possible to increase the brightness of the laser beam. Figure 2 gives data characterizing the efficiency of spatial filters.

A major step in controlling self-focusing of the emission is restricting the total length of active elements to values considerably less than the length of self-focusing of the emission. This requires the use of an active medium with large values for specific reserve (removable) energy and the amplification factor. Works [28-31], which are devoted to the principles of constructing two-stage lasers on the basis of ytterbium-erbium glasses pumped by lasers on neodymium glass, show that it is possible to realize such conditions in these systems.

On the basis of these works as well as research to insure a high emission contrast (for example, see [32, 33]), efficient conversion of the emission of a neodymium laser to the second and fourth harmonics [34], and various other studies, development has been begun on a six-channel laser device based on neodymium glass which provides control of time characteristics of emission, for emission energy up to 10^3 Joules, (including control of the profile of the pulse) in the range 10^{-10} - 10^{-9} seconds, an angular divergence up to $3 \cdot 10^{-4}$ radians, obtaining powerful emission at wavelengths of 0.53 and 0.265 microns, and a possibility of concentrating emission on objects up to 100 microns in size with a variation not exceeding 20 percent [35, 36].

Dynamic Correction of the Wave Front of Emission

In recent years a promising new way to obtain narrowly directed beams of laser emission has begun to develop: dynamic correction of wave

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fronts. The essential process is using nonlinear optical techniques to correct distortions of the wave front that occur when the emission is propagated both within the laser itself and on the path of propagation of the beam. The primary impetus to work in this direction was the discovery by associates at the Physics Institute imeni P. N. Lebedev of the Academy of Sciences USSR of the effect of reversing the wave front in induced Mandel'shtam-Brillouin scattering [37, 38]. If a single-mode signal is sent on a path opposite to the direction of propagation of the primary, powerful signal, after traveling this path its wave front will be distorted as the result of various types of disturbances and heterogeneities. Then if during reverse scattering in a forced Mandel'shtam-Brillouin scattering cell this distorted wave front is regenerated and we use the reverse-scattered signal as a "bare" signal, after traveling the entire route a powerful single-mode pulse of emission will be received at the output. In addition to the technique of reversing the wave front, which work [39] proposed for use for dynamic correction of wave fronts, the method of averaging may be used for the same purpose. The essential thing in this technique is "converting" multimode energy by pumping into a single-mode signal that is amplified during forced scattering [40, 44, 45].

Without dwelling on all the projects underway at the institute concerned with dynamic correction of wave fronts (for example, see [41-43]), we will take note of those that may be interesting in building lasers of the type under consideration here. They are investigating correction of wave fronts by the technique of reversing on the basis of the forced Mandel'shtam-Brillouin scattering and the method of averaging. A number of rules and conditions for effective reversal of the wave of short pulses for forced Mandel'shtam-Brillouin scattering in liquids have been established. Nonlinear processes in forced combined scattering in compressed gases are under study. An experimental investigation has been made of the conditions for effective amplification of a single-mode Stokes signal in a field of multimode spatially non-coherent pumping. Figure 3 (below) gives a chart of an experiment to convert a pulse with a distorted wave front into a single-mode pulse by the method of averaging with forced combined scattering in compressed nitrogen. An etched glass plate was used as an element to simulate distortion of the wave front of the emission pulse. Figure 4 (below) shows the dependence of the ratio of amplified energy of emission of a Stokes signal contained in the angle $\phi \approx 5 \cdot 10^{-4}$ radians to full amplified energy of the Stokes signal on pumping energy (the angle of divergence of pumping emissions $\theta \approx 10^{-2}$ radians). One can see that under the experimental conditions selected, averaging has an effect when $E_{\text{HAK}} < 250$ megajoules and amplification of brightness is about 10^3 .

The results that have been obtained allow us to hope that the averaging method will prove a promising means of controlling effects related to the self-focusing of powerful supershort emission pulses.

This survey of work does not, of course, exhaust all the problems now being worked on at numerous laboratories throughout the world. At the

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HIGH-ENERGY DEVICES, OPTICS AND PHOTOGRAPHY

UDC 621.384.326.22.528.7

HEAT SPECTRAL ZONE AERIAL PHOTOGRAPHY: POSSIBILITIES AND PROSPECTS

Leningrad OPTIKO-MEKHANICHESKAYA PROMYSHLENNOST' in Russian No 1, 1979
pp 18-20

[Article by candidate of sciences Ye. Ya. Karizhenskiy, doctor of sciences M. M. Miroshnikov, and candidate of sciences B. V. Shilin]

[Text] In recent years a new method of remote study of natural resources, heat aerial photography, has found increasing practical application. It is based on experience using aircraft heat sensors that record the infrared radiation of the earth's surface within the limits of some "window" of transparency in the atmosphere (3-5 or 8-13 microns) [1]. However, the diversity of temperature settings and objects studied by heat aerial photography and certain characteristics of systems for processing output data with contemporary heat sensors (in particular the limited dynamic range) do not always make it possible to obtain optimal results of recording radiation in just one spectral range.

The need to use heat sensors that record infrared radiation in the 8-13 micron interval arises from the fact that the maximum spectral density of radiation of most elements of the aerial landscape occurs in this segment of the spectrum. Studies of the ratios between the spectral sensitivity of contemporary selective photoelectric sensors and the distribution of energy of emission by wavelengths and "windows" of atmospheric transparency show [3] that when studying anomalous objects and heated backgrounds (below 20-40 degrees C., but this ratio may vary somewhat depending on the type of detector), preference should be given to heat sensors with a sensing device that has an area of spectral sensitivity of 3-5 microns (InSb). But if the object of aerial photography is small temperature drops against mildly heated and cold backgrounds (about 20-40 degrees C.), a sensing device with an area of spectral sensitivity of 8-13 microns (GeAu, HgCdTe) gives much better results, and with a drop in the temperature of the background the difference in quality of output data (reproduction of details of the landscape) between sensing devices with spectral sensitivity of 3-5 microns and 8-13 microns will be more noticeable.

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Under real conditions any landscape-climatic zone will have various types of objects of observation and backgrounds, so to study natural resources it is optimal to use an aircraft device that records infrared radiation in several zones within the limits of the "windows" of transparency at 3-5 and 8-13 microns. The device should have a minimum of two channels.

Let us illustrate the advantages of two-zone heat sensors with concrete examples of studying weakly heated backgrounds and anomalous objects. Figure 1 [see page below] shows heat aerial photographs of a landscape segment in the non-chernozem zone of the RSFSR in the spectral intervals 8-13 and 3-5 microns taken at night. A land reclamation system with open and closed drainage, represented by a drained low peat bog, occupies the middle of the picture. The system is crossed by the collector stream 1 which flows into lake 5 (near the right edge of the photograph). The reclamation system is surrounded by conifer forests 4; a village and gardens are located along the top edge and highway 2 is easily visible.

On a clear summer night the land temperature began to drop rapidly (6-10 degrees) because of radiation cooling and a water-land inversion developed. The lake in the photograph looks very warm, light (18-20 degrees C.). The conifer forests and gardens also appear warm because vegetation regulates its own temperature and cools off at night much more slowly than soil and rock. Thus, in radiation conditions the coldest (darkest) parts of the photographs are segments of exposed or grass-covered soil within the reclamation system and the warmest are the bodies of water and highway which accumulate solar heat very well.

If all the heated objects in both aerial photographs are processed in approximately the same manner (in a channel working in the range 3-5 microns it is not quite as good owing to slight loss of focus on the image), there are significant differences in the image of the cold background of the reclamation system. In the aerial photograph obtained with the channel working in the interval 8-13 microns differences in the humidity of the fields (or the condition of the grass cover), drainage canals of different sizes, the main collector stream 1, and segments linked with the discharge of groundwater 3 are visible. In the aerial photograph obtained using the 3-5 micron channel no details at all stand out within the reclamation system; only the heated segments of groundwater discharge are faintly visible.

Similar patterns were found for other types of "cold" landscapes, for example snow and ice covers on land and sea. All this illustrates the significant advantages of a channel working in the range 8-13 microns for studying cold backgrounds.

When the technique of heat aerial photography is used to study natural and manmade objects on the surface which have their own anomalous heating (active volcanos, zones of vigorous hydrothermal activity, forest fires, operating industrial structures, and the like), data on the internal thermal structure of the object, that is, information on the

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intensity of heating of its particular elements, is especially important. But at the same time, the heat aerial photograph must contain adequately detailed information about the surrounding landscape for correct alignment of the anomalous objects with the terrain.

The limited dynamic range of one-channel heat sensors and certain other shortcomings that they have make it impossible to receive all the data listed above. If the device is adjusted (level of alignment-brightness and videoamplification-contrast) for optimal representation of the landscape, anomalous objects will be outside the dynamic range of the cathode ray tube-photographic film system and during interpretation may be missed in the "noise" background caused by relatively mildly heated landscape elements (slopes with different daytime exposures, bodies of water and vegetation at night, and the like).

When the device is tuned for anomalous objects the surrounding landscape will not be depicted and the position of the objects will not be defined. If the problem being solved is not limited by a time framework, it is possible to make a series of flights over the anomalous object with different tunings. For example, forest fires, hydrothermal fields, and active volcanos in Kamchatka have been studied with one-channel devices [2]. In many cases the technique of repeated flights is completely inapplicable and the necessary information must be obtained in one flight over the situation under study.

In principle it is possible here to use a heat sensor with two identical channels calculated for the 3-5 micron range, with one set for landscape, the other for anomalous targets. However, in this case the cold backgrounds of landscape detail in the photograph will process poorly and interpretation may be complicated. But if two channels working in the 8-13 micron range with the same setting for background and anomalous objects are used, difficulties of a different type may be encountered. For example, when identifying sources of incipient forest fires, "point" objects with temperatures of more than 600 degrees C., their image on the heat aerial photograph may not have adequate contrast and be missed in interpretation. This is because the "point" fire occupies only a small part of the instantaneous field of vision of the receiving system and the flux from this target is a part of the flux being recorded. With recording in the 3-5 micron range such an object is depicted with greater contrast owing to better alignment of the characteristics of study of the source and the detector (usually InSb) working in this range. Considerably better results can be obtained by combining, for example, a terrain image in the 8.5-11 micron zone with an image of the source received by subtracting from the signal corresponding to the 3-4 micron zone of a signal corresponding to the 8.5-11 micron zone [4].

As an example of recording of anomalous objects Figure 2 [see next page] gives two daytime heat aerial photographs of hydrothermal shows in Uzon Caldera on Kamchatka (the top photograph is in the 8-13 micron range and the bottom one is 3-5 microns). The channel working in the 8-13 micron interval was tuned for the landscape and the 3-5 micron channel was set

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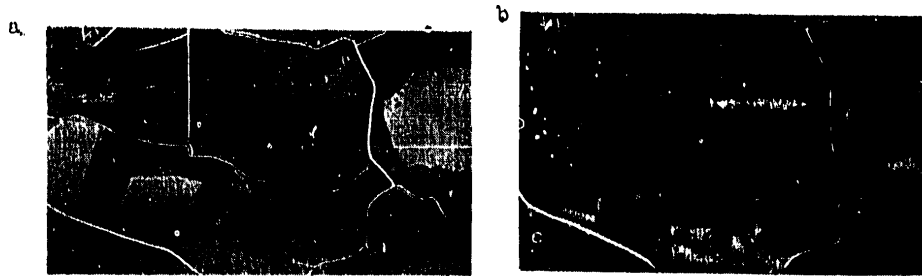


Figure 1. Heat Aerial Photographs Taken with a Two-Channel Vulkan Heat Sensor at Night (scale of 1:25,000): a -- spectral interval 8-13 microns; b -- 3.2-5.3 microns; time of photography 2134; flight altitude 1,000 meters.

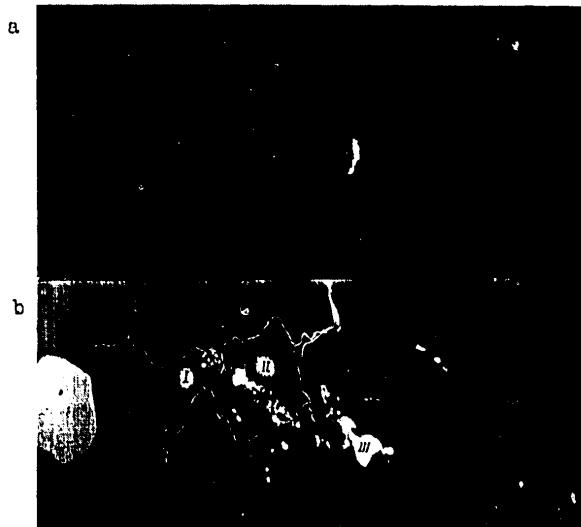
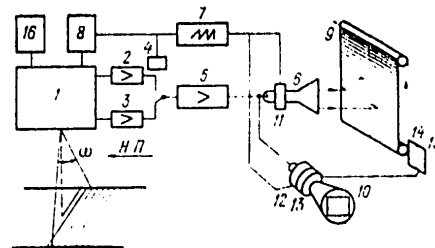


Figure 2. Daytime Heat Aerial Photographs Taken with Two-Channel Vulkan Heat Sensor (scale of 1:45,000): a -- spectral interval 8-13 microns; b -- 3.2-5.3 microns; time of photography -- 1840; flight altitude -- 1,500 meters.

Figure 3. Structural Diagram of Two-Zone Heat Sensor



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for anomalous hydrothermal objects (temperatures from 20 to 100 degrees C.). In the heat photograph corresponding to the 8-13 micron range all the details of the generally "cold" landscape (a thin layer of snow covered the surface shortly before the photograph) processed quite well and it is not difficult to recognize the situation.

Because of the deep water-land inversion, not only all the thermal shows of the caldera but also the cold streams and lakes (in the right part of the photograph) are represented as anomalously heated. Interpretation of aerial photograph 2a does not permit an unambiguous conclusion about the thermal nature of all anomalous objects identified; discharges of warm water into the central lake are an exception.

The aerial photograph obtained using a channel working in the 3-5 micron range provides information on thermal shows with large heat discharge. In this photograph only such objects have bright, characteristic signals. Despite the fact that Figure 2b does not contain the slightest suggestion of landscape, it is quite easy to recognize the anomalous objects on the terrain using parallel aerial photographs obtained by means of both channels and recorded on one film.

It was possible to single out the most active thermal shows within the basic thermal fields of the caldera. In the eastern field (I in Figure 2a) there are three large thermal shows that form a small chain arranged approximately in a north-south direction and connected to the hot pools and gas-vapor jets. In the central field II the eastern part is most active; a very small cove can be seen on the north shore of Fumarol'noye Lake III. In the group of thermal shows north of the central field the isomeric thermal show related to the hot mud lake, which is discharging a large amount of heated vapors and gases, is especially vigorous. It does not stand out in any way among the four thermal shows of this group in aerial photograph 2a. Similar materials were obtained from study of active volcanos and industrial complexes with operating power plants.

The aircraft heat sensors Teplo-4 and Vulkan that have now been built and are designed to study natural resources and geological-geographic features insure receipt of images simultaneously in any two zones related to the ranges 3-5 and 8-13 microns. The zones are selected by putting the appropriate light filters in front of the receivers. Both heat sensors are based on the same schematic diagram (Figure 3 on preceding page).

Scanning system 1 receives the optical emission from the aerial landscape in conformity with the law of scanning sighting rays and converts the emission into signals. These signals go from the output of the detectors to preamplifiers 2 and 3, and then through the contacts of switch 4 to the input of videoamplifier 5, whose output is connected with the modulating electrode of the cathode ray tube 6, the photographic device, and tube 10, which is the video monitor. Line scanning of the image on the screens of these tubes is done by means of deflecting coils 11 and 12, which are connected to pulse generator 7. The generator, like switch 4, is synchronized with scanning system 1 by means of synchronization sensor 8. The image from the screen of cathode ray tube 6 is

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transferred to photographic film 9, which is moved (by-frame image scanning) at a rate proportional to the quantity w/H where w is the ground speed of the aircraft and H is the true flight elevation. The photographic film is moved by electric drive 14. Current generator 15, connected to frame coil 13 of cathode ray tube 10, is synchronized with electric drive 14. Individual images corresponding to each channel are obtained on the photographic film by switching lines in the cathode ray tube with the same frequency that the channels are switched by switch 4. A visible image of the frame is obtained on the screen of cathode ray tube 10 through the prolonged afterglow on the screen of this tube, which helps the operator monitor the work of the device and the course of aerial photographic work. The camera cooling system 16 is connected to scanning system 1.

As an example, let us consider the characteristics of the Vulkan heat sensor, which matches the best world models for instruments of this type.

Basic Technical Features of the Vulkan Heat Sensor

Angle of Aspect	80 angular degrees
Instantaneous Viewing Angle (resolution)	7 angular minutes
Number of Channels	2
Temperature Sensitivity Against a Background of 20° C.	
3-5 Micron Channel	0.5 degree
8-13 Micron Channel	0.25 degree
Speed w/H	0.3 1/sec
Weight of Unit	195 kg
Cooling System Open-Type (liquid nitrogen)	

The next stage in the development of heat aerial photography as a method of studying natural resources is the use of devices with a large number of channels. On this level, devising a spectral zone measurement unit with, for example, six channels based on the use of one nonselective detector (a high-speed, superconducting bolometer) will make it possible to select the required zones by simply putting the appropriate filters in the receiving unit, which greatly simplifies the circuitry and design of the device itself and reduces the effect of errors by using one general amplification-recording line for all channels. Working with several regulated channels corresponding, for example, to the narrow zones of the 8-13 micron "window" will make it possible to record a minimum on the curve of spectral density of emissions around 10 microns. The amplitude and position of this minimum are related to the content of silica in the top layer of soil and rock. In addition, this device will make it possible to solve the inverse problem of heat aerial photography as a geophysical method of remote determination of heat physics characteristics (heat energy) in soils and rocks. Use of the spectral zone method in remote probing also offers the possibility of improving the precision of measurement of the temperature of natural objects by minimizing the destabilizing effect of the atmosphere in the process of recording the stream of rays [5].

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FOOTNOTES

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HIGH-ENERGY DEVICES, OPTICS AND PHOTOGRAPHY

UDC 535.361.21

REFLECTION OF LIGHT BY A ROUGH SURFACE

Leningrad OPTIKO-MEKHANICHESKAYA PROMYSHLENNOST' in Russian No 1, 1979
pp 34-46

[Article by doctor of sciences A. S. Toporets]

[Text] Interest in the reflection of light by rough surfaces began in Buger's times [1]. Buger initiated the tone-photometric technique and introduced the concept of the indicatrix. According to his ideas, a rough surface is formed of microfacets set at various angles of the macro-surface and a study of the distribution of these facets according to their orientation makes it possible to find the laws of light reflection by this surface. In other words, the distribution of light reflected by a rough surface is a result of its topography. Buger thought that each microfacet reflected light like a mirror, and therefore that the distribution of scattered light in space was related to the function of distribution of the microfacets by angles of inclination. This function may be found experimentally if the surface is illuminated by a beam that is close to parallel and the force of the light reflected in a direction opposite to the direction of fall is measured.

Contemporary authors engaged in studying the reflection of light by rough surfaces share Buger's ideas. In this respect we may mention the work of Berry [2], Pokrowski [3], Ornstein and van der Burg [4], Barkas [5], Gorodinskiy [6], Mullamaa [7], Torrance and Sparrow [8], and Gershun and Popov [9]. All of these works typically solve the problem from the standpoint of geometric optics, which limits the area of application of results obtained to the domain in which the dimensions of the light-reflecting elements significantly exceed the length of the light wave.

One can imagine many types of rough surfaces, both regular (for example diffraction grids and screens) as well as irregular surfaces with different distributions of roughness. In what follows we will deal with surfaces formed by the work of a free abrasive. In general they will be metallic or glass surfaces covered with a fine metal film.

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As the natural boundary of a physical body, the surface possesses to some extent the properties of the body itself and at the same time has its own properties because the particles that form it are at the meeting point of two media that differ by physical properties. A special characteristic of a rough surface is its microgeometry, represented by an assemblage of depressions and protuberances which usually have random dimensions and random mutual arrangement. Such a surface can be characterized by a profile which is recorded either by means of a profile plotter or by the shade method. Figure 1 shows the profile of a glass surface worked by M7 abrasive powder. The recorded profile allows an estimation of the quantitative parameters of the properties of the rough surface. Among these parameters are [10] R_a — the average deviation of points on the profile from the median line and R_z — the average difference in the heights of the five highest and five lowest points on the base length of the profile.



Figure 1. Profile of A Rough Surface (ratio of vertical enlargement to horizontal — 50)

We will see later that there is a correlation between these parameters and that the amount of light reflected by a rough surface and its distribution in space are dependent on its parameters and the parameters of the emission striking it.

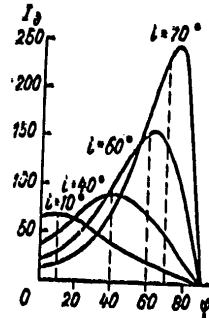
Diffuse Reflection

When a plane wave strikes a rough surface, the front of the reflected wave is broken into many small segments, each of which has its own direction. If the distribution of microareas has amplitudinal symmetry, when light strikes the surface normally the body of dispersion forms as a body of rotation. In this case, exhaustive energy information may be obtained by recording the indicatrix of dispersion in one plane.

Figure 2 below shows the indicatrices of diffusely reflected light corresponding to a glass plate whose surface has been worked with M28 abrasive and coated with a thin layer of aluminum. The average height of rough places h is 2.86 microns. We see that for small angles the maximum of light reflection coincides with the direction of the mirror reflection, but beginning at about 40 degrees these maximums shift toward the larger angles. In other cases it is possible to observe a shift of the diffuse maximum toward smaller angles also [11, 12]. The fact that the maximum angular density of the reflected flux is observed close to or exactly in the direction of the mirror reflection may be explained by the fact that the largest relative number of microareas of a rough surface are oriented so that perpendicular lines to them are arranged close to

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Figure 2. Indicatrixes of Reflected Light for Angles of Arrival 10, 40, 50, and 70 Degrees.



perpendicular to the surface. Only these areas can reflect light in the mirror direction or close to it. Figure 3 shows curves that characterize the distribution of microareas by angles of inclination for glass surfaces worked with abrasives Nos 6 and 8 and covered with a fine coat of aluminum [13]. The curves have two fields: a — the small-angle field

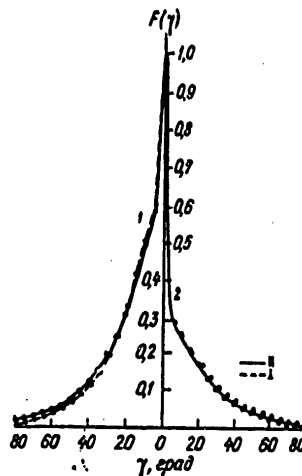


Figure 3. Distribution Function of Microfacets by Angles of Inclination of Rough Surfaces Worked with Abrasives No 6 (1) and 8 (2).

which covers 3-5 degrees from the perpendicular, in which a sharp drop in values relative to the distribution function is observed, and b — all the rest of the angular field in which the curve of distribution closely approximates an exponential curve. These results are confirmed by studies of the dispersion of light that has passed through the rough surface of a glass [14]. In this case also the curve of dispersion is close to exponential and the rougher the surface is the closer it comes. In the

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small-angle field the curve of dispersion also deviates from the general pattern: a sharper drop is observed than required in the case of the exponential curve.

Finding the distribution function of the microfacets according to angles of inclination by the Bugar method is based on the laws of geometric optics and will be valid only where the dimensions of the microfacets significantly exceed the wavelength of the incoming light. But when the dimensions of the rough places are compatible with the wavelength, the distribution of reflected light governed by the inclination of the microfacets is distorted by diffraction, especially in the field of large angles of arrival and observation. In this case we observe a greater amount of dispersed light than should occur according to the geometry of dispersion.

Assuming that reflection occurs according to the laws of geometric optics, we can write the expression for the flux reflected within a small space angle $\Delta\omega$ in the mirror direction.

In the case of amplitudinal symmetry the distribution of microareas by angles of inclination is expressed by the function

$$f(\delta) = \frac{\Delta S_\delta \cos \delta}{S_0 \Delta \omega}.$$

In this equation δ is the angle of inclination of the microperpendiculars to the macroperpendicular; F_0 is an area of the surface illuminated on the perpendicular; $\Delta S_\delta \cos \delta$ is the area of projections of the microareas inclined at angle δ to the macrosurface; $\Delta\omega$ is the space angle within which the perpendiculars to these microareas near the direction defined by angle δ are located.

Suppose that light stream Φ_0 strikes the surface at angle ψ and the part of this flux striking the microareas that interest us, $\Delta\Phi_0$, is

$$\Delta\Phi_0 = \Phi_0 \frac{\Delta S_\delta \cos \delta \cos \psi}{S_0 \cos \psi} = \Phi_0 f(\delta) \Delta\omega.$$

The flux reflected from these microareas at angle $\theta = \psi$ is $\Delta\Phi_{\text{отр}} = R_0 \Phi_0 f(\delta) \Delta\omega$.

Experience shows that the diffuse maximum grows much more rapidly than the coefficient of reflection R_0 as the angle of arrival increases. This can be explained as follows. When the illuminating beam is slanted the body of dispersion assumes a flatter shape, contracting toward the plane of incidence. For example, when light strikes on the perpendicular the body of dispersion has the shape of a body of rotation, but at angles greater than 40 degrees it assumes a flattened shape. The planes of reflection of elementary beams are turned so that the angle between these planes and the primary plane of incidence decreases as the slant of the illuminating beam increases. At the same time, owing to diffraction the reflected beams propagated in adjacent

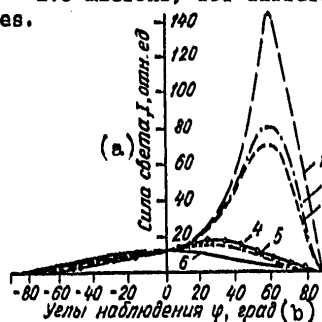
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planes to some extent overlap. Thus, the density of the reflected flux in the plane of incidence increases at the expense of adjacent areas [11].

The flattening of the indicatrix of dispersion toward the plane of incidence is illustrated in Figure 4 below, which gives the indicatrices of dispersion of light by a rough metallic surface ($h = 1.3$ microns) for different azimuths with an angle of incidence of 60 degrees.

Figure 4. Indicatrixes of Dispersion of Light by a Glass Surface Worked with M7 Abrasives and Coated with Aluminum. Angle of Incidence Is 60 Degrees; Wave Length Is 550 Nanometers. Azimuthal Angles: 1 -- 0-180°; 2 -- 170-350°; 3 -- 10-190°; 4 -- 135-315°; 5 -- 45-225°; 6 -- 90-270°.

Key: (a) Luminosity I , relative units;
(b) Angles of Observation ψ , degrees.



We see that the luminosity at the maximum for an azimuth of 10 degrees is about half of its value in the plane of incidence. For an azimuth of 90 degrees it is more than an order smaller; in this case the curve of dispersion is symmetrical relative to the perpendicular [15].

The behavior of the diffuse maximum changes greatly when the mirror reflection is observed next to the diffuse one. Figure 5 shows three series of indicatrixes of one test piece with an average height of roughness of 1.3 microns. The series were recorded for the wave lengths: 0.5, 1.0, and 2.0 microns. It is noteworthy that the mutual positions of the mirror and diffuse maximums change with change in the angle of incidence. Moreover, we see that at first the diffuse maximum grows and at a certain angle of incidence reaches its greatest value. Then it begins to decrease and shifts in the direction of smaller angles relative to the mirror reflection. Figure 6 (next page) shows the relationship between the magnitude of the diffuse maximum and the angle of incidence for aluminum-coated glass surfaces with average heights of roughness of 0.75, 1.25, 2.86, and 5.4 microns with a wave length of 0.63 microns. The angle at which the diffuse maximum

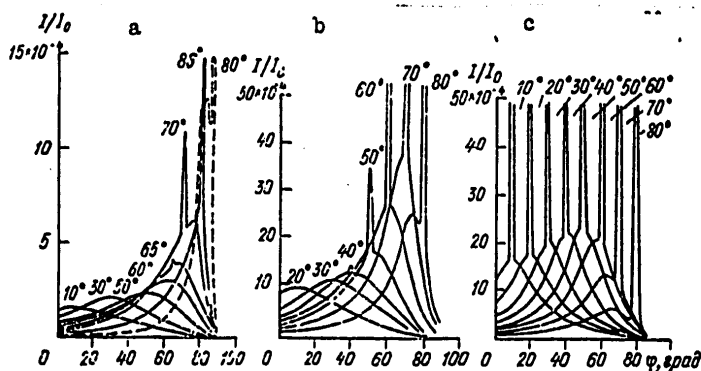
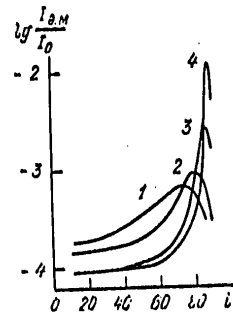


Figure 5. Indicatrixes of Light Reflected from an Aluminum-Coated Glass Surface Worked with M7 Abrasive: a -- $\lambda = 0.5\mu$;
b -- $\lambda = 1.0\mu$;
c -- $\lambda = 2.0\mu$.

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Figure 6. Dependence of the Magnitude of the Diffuse Maximum on the Angle of Incidence for Surfaces Worked with Abrasives: 1 - M5; 2 - M7; 3 - M28; 4 - No 5; $\lambda = 630$ Nanometers.



reaches its greatest value for each test piece is defined by the following condition:

$$\cos \psi = p \frac{\lambda}{h}, \quad (1)$$

where $p = 0.388$. It follows from (1) that the greater the wavelength is, the smaller the angle should be at which the marginal value of the diffuse maximum of the given surface is observed. Thus, where $h = 0.25$ microns and $\lambda = 0.63$ microns, the marginal value of the diffuse maximum should be observed at an angle $\psi = 10$ degrees while for a test piece with an average roughness of 5.4 microns it is observed at an angle of $87^\circ 35'$. The diffuse maximum always coincides with the mirror maximum for a polished surface.

The Mirror Reflection

If we take a polished glass or metal plate as a rough surface and observe light reflected by its surface at large angles, we can ascertain that the image of the source of emission is visible in the range of angles 80-88 degrees. At first it appears unclear, but as the angle increases it becomes more distinct and even takes on various colors.

In his day Rayleigh showed [17] that to receive an adequately sharp image from a rough surface it is necessary that the maximum difference in the path of any pair of rays reflected by this surface not exceed $\lambda/4$,

$$2h \cos \phi \leq \lambda/4, \quad (2)$$

where h is the height of roughness from the bottom of the depression to the peak of the protrusion; ψ is the angle of incidence of the rays. It follows from (2) that the quality of a mirror is determined not by the roughness of the surface, but by the wavelength of the emission striking it. Thus, rolled sheet metal may be a good mirror for the

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infrared range of the spectrum but at the same time scatter light in the visible range diffusely.

The critical angle method. Jentsch [18], studying reflection from a rough surface, established that there is a critical angle at which the surface begins to reflect light in mirror fashion. For smaller angles of incidence most of the light is reflected diffusely. This critical angle is defined by the condition

$$p \lambda = 2h \cos \psi,$$

where, following Rayleigh, Jentsch takes $p = 1/4$.

An experimental device was assembled to measure the critical angle. The image of an illuminated slot formed by rays reflected by a rough surface was observed by means of an ocular in the focal plane of the objective of a microscope; the angle of incidence of the rays on the rough surface could be changed, as could the angle of observation. At a certain angle of incidence ψ the image of the illuminated slot appeared; in one half of the field of vision of the ocular it was sharp, while in the other half it was diffuse. The difference was explained by the fact that the rays formed by the image in different halves of the field of vision were reflected from the rough surface at different angles.

Jentsch's experiments were repeated 13 years later by Hasunuma and Nara [19] in somewhat altered form. The experimental device was built in two variations: for visual observations and objective measurements using a photomultiplier. The critical angle at which the image of things became sharp was also observed. The divergence of the beam of light carrying the image was about one degree.

Studying the relation between the intensity of light reflected near this angle and the magnitude of roughness of the surface they confirmed the condition of appearance of the mirror component found by Jentsch.

$$2h \cos \phi = \lambda/k. \quad (3)$$

In this expression the constant k for various metals proved different. For steel it was about three, but for chrome-plated bronze it was two. In addition, the researchers found that its value depends somewhat on the grinding process.

Formula (3) permits a greater difference in the path for formation of the mirror component than the Rayleigh formula.

In an effort to give a theoretical interpretation of the results obtained, the authors assumed that a metal surface worked by a free abrasive has a profile whose high points are random functions of coordinates and can be assigned statistically. Working from this for light scattered by a rough surface, a formula was found in which the mirror and diffuse components found their own expressions in the form of distinct members.

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In our times experiments to determine the average height of roughness visually have been repeated in work [20]. It seems to us that the procedure for estimating the so-called critical angle in which the eye is supposed to see the image of a thing or slot against a background created by dispersed light is less sensitive than the use of indicatrices. With this method it is possible to evaluate the mirror component with an intensity no greater than 1-2 percent of the intensity of the diffuse background.

The indicatrix method. In the works we will be discussing reflection from a rough surface was studied by means of the indicatrix method. A goniospectrophotometric device with an angle resolution of a few angular minutes was used for this. The optical chart of this device is shown in Figure 7 below. The beam emerging from the monochromatic

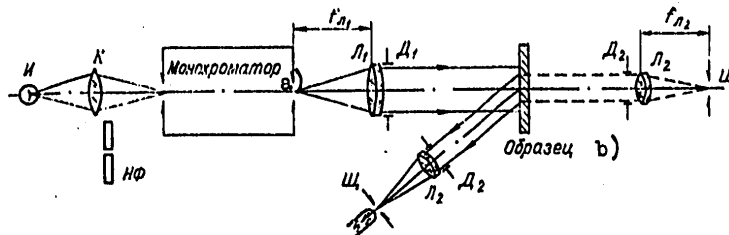


Figure 7. Optical Chart of A Goniospectrophotometric Device with High Angle Resolution

Key: (a) Monochromatic Illuminator;
(b) Sample Piece.

illuminator is shaped by objective Π_1 ; the divergence of the beam in the plane of incidence is determined by the focusing distance of this objective (250 millimeters) and the width of the output slot of the illuminator. The reflected beam within the limits of the small space angle is overlapped by objective Π_2 , which has the same luminosity as Π_1 and is focused in the plane of receiving slot $\mathcal{W}$. A mat-surface glass and photomultiplier are placed behind the slot. The electrical signal from the photomultiplier is fed to a self-recording potentiometer. An electric motor shifts the entire receiving system in a circle, and the self-recorder records a continuous curve on tape. This is the indicatrix of dispersion [21].

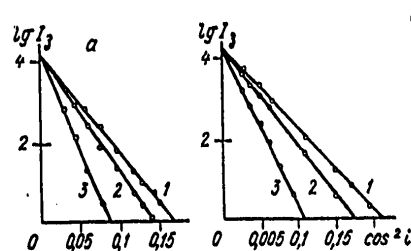
The curves shown in Figure 5 above were obtained by using this device. Its sensitivity made it possible to record indicatrices with angle resolution of three angular minutes, and therefore it was possible to follow in some detail the development of the mirror component of the

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reflected flux as the angle of incidence of the light was increased. The figure shows that a small critical maximum (peak) appears on the curve of diffusely reflected light beginning at a certain angle of incidence and the middle of this peak coincides with the direction of mirror reflection. As the angle of incidence is increased this maximum grows rapidly. Its magnitude is not determined by the angle of incidence alone; it also depends on the wavelength of incoming light. This can be determined easily by comparing Figures 5a, 5b, and 5c. They were obtained with illumination by light with wavelengths 0.5, 1.0, and 2.0 microns. The greater the wavelength, the smaller the angle at which the mirror component appears. It turned out that the ratio of wavelength to the cosine of this angle was a constant value for the given surface. If these ratios are compared for different surfaces, it may be seen that they are interrelated as average heights of roughness.

Figure 8 below shows graphs that characterize the dependence of the intensity of the mirror component on the angle of incidence of light for metallic surfaces. The square of the cosine of the angle of incidence

Figure 8. Dependence of $\lg I_3$ on $\cos^2 i$ for Metallic Surfaces Worked by M-14 (Part a) and No 3 (Part b) Abrasive Powders:
1 — $\lambda = 620$ nm; 2 — $\lambda = 550$ nm;
3 — $\lambda = 450$ nm.



is laid out on the X axis and the logarithm of intensity of the mirror component is shown on the Y axis. The relationship is the same for a dielectric surface and a metallic surface. This shows that the determining factor is not the material but rather the geometry of the surface. The fact that the lines related to different wavelengths are intersected at the same point suggests that they can be reduced to a single angular coefficient. Indeed, if we take $\cos^2 \psi / \lambda^2$, then the points of the three lines depicted in Figure 8 are sufficiently close to a straight line [22].

Processing data obtained for a large number of different sample pieces made it possible to express the dependence of the intensity of the mirror component I_s on the cosine of the angle of incidence, wavelength of incoming light, and average height of roughness as follows

$$I_s = \bar{p} I_e e^{-k \frac{h^2}{\lambda^2} \cos^2 \psi} \quad (4)$$

The magnitude of the constant k was determined from experimental results and proved to be equal to $9.8 (\pi^2)$.

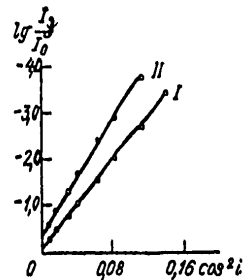
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Thus, the intensity of the mirror component of a flux reflected from a rough surface is an exponential function of the parameter $h/\lambda \cos \psi$. When light is reflected it is not only dispersed but also weakened, and the coefficient of reflection is a measure of this. In formula (4) it is designated by the symbol p and called effective; it is not equal to the coefficient of mirror reflection, generally being smaller. For the metallic surfaces studied it was constant in a broad range of angles.

The multiplier $e^{-\frac{h}{\lambda} \cos \psi}$ has received the name mirror coefficient because it shows what fraction of the light reflected by a rough surface is reflected in mirror fashion. This coefficient depends entirely on the microgeometry of the surface and the wavelength of incoming light. But the optical properties of the reflecting substance are contained in the coefficient of reflection $\bar{p}$.

Studies of the mirror component were also made with polarizing light [23]. Figure 9 presents certain results as an example.

Figure 9. Dependence of $\lg I_3/I_0$ on $\cos^2 i$ or a Surface Worked with M7 Abrasive and an Aluminum Surface.



The square of the cosine of the angle of incidence is laid out on the X axis and the Y axis shows the logarithm of the ratio of the intensity of the mirror component to the intensity of incoming light. As before, this relationship is expressed by a straight line. The only difference is that each component has its own straight line. These lines are somewhat shifted relative to one another and have slightly different slants. The shift does not occur in all cases. For surfaces worked by coarse abrasives the points for both components lie on the same line. The segments cut off by a continuation of the straight lines to the Y axis give the quantity $\lg \bar{p}$, and with this it is not difficult to find the effective coefficient of reflection. It turned out that these coefficients for both types of surfaces differ significantly from the values of the coefficients of mirror reflection.

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Using formula (4) it is possible to determine the magnitude of the mirror coefficient, assigning the values of average height h , wavelength λ , and the angle of incidence. For example, if $h \cos \psi / \lambda = 0.5$, the mirror coefficient is eight percent, but when this factor is equal to 0.05 the amount of light reflected in mirror fashion reaches 97 percent. In other words, the rough surface reflects light like a mirror.

In the case where the mirror component is large ($h \cos \psi / \lambda \ll 1$), the expression for the mirror coefficient may be expanded to a series by degrees of $h \cos \psi / \lambda$. Limiting ourselves to the first two terms, we receive

$$e^{-\frac{\pi^2 h^2}{\lambda^2} \cos^2 \psi} \approx 1 - \frac{\pi^2 h^2}{\lambda^2} \cos^2 \psi.$$

Then formula (4) takes the form $I_s = \rho I_0 \left(1 - \frac{\pi^2 h^2}{\lambda^2} \cos^2 \psi \right)$.

In this case the second term gives the intensity of dispersed light

$$I_d = \rho I_0 \frac{\pi^2 h^2}{\lambda^2} \cos^2 \psi. \quad (5)$$

Therefore, when the mirror component is large, the intensity of light dispersed within the space angle 2π is proportional to the square of optical roughness $[h/\lambda]$.* This is a very important result because it shows that there is a simple relationship between the amount of diffusely scattered light and the optical roughness [16]. Moreover, it follows from (5) that the amount of diffusely scattered light is proportional to the square of the cosine of the angle of incidence. Thus, with an angle of incidence of 70 degrees only about 1/10 as much light is dispersed as when light falls on the perpendicular.

The method of comparing coefficients of mirror reflection with perpendicular arrival. Bennet and Porteus used a different method to study the reflection of light by a rough surface [24, 25]. They developed a spectral photometer that could measure the coefficient of mirror reflection with a precision down to 0.1 percent for work in the infrared range of the spectrum [26]. This instrument was used to measure the coefficient of mirror reflection of test pieces made of steel and glass and then coated with aluminum. The samples were roughened with grinding powders that had particle sizes of 5-22 microns, and some were also polished.

The authors employed a theory developed by Davies [27] for radar waves reflected by an agitated water surface. It followed from this theory that the amount of energy reflected in mirror fashion is an exponential function of the parameters of the surface and the emission. When the emission strikes a surface perpendicularly the coefficient of mirror

* We use the term "optical roughness" for the ratio of average height of roughness to the wavelength of incoming light.

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reflection p_g is expressed as follows $p_g = p_0 e^{-\left(\frac{4\sigma^2}{\lambda}\right)}$.

In this p_0 is the coefficient of mirror reflection of a perfectly smooth surface of a piece of the same material; σ is the mean quadratic deviation from the average line of the profile; λ is the wavelength of the incoming emission. For a diffusely scattered emission it is possible to write an expression which contains, in addition to σ and λ , the mean quadratic inclination of the profile. Assuming in measurement of the mirror reflected emission that a certain part of the diffusely reflected emission also strikes the energy detector, the authors derived a general expression that includes both components of a reflected emission:

$$\rho = p_0 e^{-\left(\frac{4\sigma^2}{\lambda}\right)} + p_0 \gamma p_d, \quad (6)$$

where p_d is the coefficient of diffuse reflection in a hemisphere and γ is a certain coefficient less than one that depends on the space angle of the receiving device and the indicatrix of dispersion. For quite large wavelengths where $\sigma/\lambda \ll 1$, the first term in expression (6) assumes a large value while the second is small beyond measurement; then we may consider that

$$\rho \approx p_0 e^{-\left(\frac{4\sigma^2}{\lambda}\right)}.$$

Thus, having measured the coefficient of mirror reflection of a rough surface when illuminated by a monochromatic emission at a small angle to the perpendicular and knowing the coefficient of reflection of a polished surface of the same material, it is possible to estimate the mean quadratic deviation from the average length of the profile σ , which is a characteristic of the reflective properties of a rough surface:

$$\sigma = \frac{\lambda}{4\pi} \sqrt{\ln \frac{p_0}{\rho}}.$$

A comparison of experimental results with calculated data showed that only in the realm of high coefficients of reflection did the experimental points lie on the calculated curve. The authors related the divergence of data in the realm of lower values ($p_g < 0.9$) of the reflection coefficient to the second term in expression (6).

The Theory of Reflection of Light by a Rough Surface

Now let us try to understand the phenomenon of light reflection from a rough surface. We see that there are two types of reflection, mirror and diffuse. We can say that the latter always exists and there is no surface where it is absent.

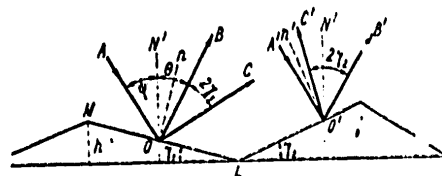
The distribution of a diffusely reflected flux in space depends on the mutual orientation of perpendiculars to the reflecting microareas and the direction of the incoming beam. When the areas are large enough the indicatrix of dispersion is related to the function of distribution of the

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microareas by angles of inclination and, if the latter is exponential, the distribution of dispersed light follows the same law. But this situation begins to break up when the dimensions of the reflecting microareas become compatible with the wavelength of the incoming emission. In this case the aperture of the reflected beams is no longer dependent on the aperture of the incoming beam, but rather is caused by diffraction. Diffraction widening will be greater when optical roughness h/λ is less.

Let us consider reflection from an elementary cell formed by two microfacets of a rough surface angles of inclination γ_1 and γ_2 (Figure 10 below). For the difference in the path of the rays that emerge from

Figure 10. Diagram of Light Reflection from an Elementary Cell of a Surface.



points O and O' and from lowest point L, we obtain the expressions

$$\Delta x_{OL} = -2l_{OL} \cos \psi \sin \gamma_1.$$

$$\Delta x_{O'L} = 2l_{O'L} \cos \psi \sin \gamma_2.$$

In this case ψ is the angle of incidence of the rays and l_{OL} and $l_{O'L}$ are the distances between points. Substituting the height of the points from a certain plane for this distance we receive

$$\Delta x_1 = -2h_1 \cos \psi.$$

$$\Delta x_2 = 2h_2 \cos \psi.$$

The difference of the path between points O and O' is equal to

$$\Delta x_1 + \Delta x_2 = 2 \cos \psi (h_2 - h_1) = 2h \cos \psi.$$

It follows from this that when a plane wave in a reflected beam strikes a rough surface, a phase difference equal to 0 will be observed for rays originating in the direction of the mirror reflection from the points located at equal distances (heights) from the planar surface. In all other cases, where $h_1 \neq h_2$, the mirror component will be formed of rays for which the difference in path meets the condition

$$2h \cos \psi \leq \lambda/2.$$

As can be seen from Figure 10, there is a significant angle between the ray reflected from the microfacet and the direction of the mirror reflection from the macrosurface. This angle is constant for different angles of incidence of the light and is equal to 2γ . Two conditions are necessary for the light to be propagated at an angle equal to the angle of incidence after reflection from a rough surface: diffraction

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of the light in the required direction and appropriate phase relations among interfering beams.

The angle of diffraction α is determined by the ratio between the wavelength and the length of an elementary facet (in the plane of incidence):*

$$\sin \frac{\alpha}{2} = \frac{\lambda}{1 \cos \psi}.$$

For rough surfaces with relatively large microfacets and random distribution of them, reflected light cannot be propagated in a mirror direction because reflection from the microfacet follows the laws of geometric optics and the angle of diffraction is too small. With an increase in the angle of incidence, when the visible dimension of the microfacets in the plane of incidence is reduced so much that the half-width of the diffraction maximum begins to overlap the angle between the direction of the mirror reflection and the direction of reflection from the microfacet, the appearance of a mirror component becomes possible. In this case the first condition is met: some part of the diffracted rays is propagated in the direction of mirror reflection. The second condition, appropriate phase ratios for ray interference, is met statistically [6].

Such in general outline is the explanation given for the origin of the mirror component of a stream reflected from a rough surface. It is relevant to add to this that another not unimportant cause of the growth of the mirror component is the flattening of the indicatrix of dispersion toward the plane of incidence, as a result of which the body of dispersion assumes an increasingly oblate form as the angle of incidence increases.

We have considered a cell in which the characterizing parameters have definite values. In reality a rough surface is a formation with random distribution of elements, protrusions and depressions, both by dimensions and by position, and the reflected beams being measured are formed of a full assemblage of these elements. The total effect of such an assemblage is usually studied by means of the mathematical apparatus of probability theory.

Numerous theoretical considerations have been undertaken of the phenomenon of reflection of the electromagnetic waves from a rough surface. In addition to works [17] and [19] which have already been mentioned, we should recall the studies by Davies [17], Beckmann [28], and Porteus [29]. Davies' work was especially popular, but in recent times Beckmann's results have gained ascendancy. Beckmann considered

* At angles $\alpha/2 < 20$ degrees, it is possible to replace the trigonometric function with its independent variable.

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the problem in its most general form, including such effects as the polarization of incoming and reflected beams, shading of some elements of the surface by other, neighboring elements, and the finite conductivity of the reflecting material. It is true that he obtained solutions only for more limited situations. It should be mentioned that both Davies and Beckmann solved the problem for radio waves.

We have already seen that the optical properties of a rough surface are generally defined by optical roughness h/λ . Where $h/\lambda \gg 1$ there is a multiple reflection between rough spots as a result of which the reflection coefficient decreases compared to the reflection coefficient of a smooth surface made of the same material. On the other hand, when $h/\lambda \ll 1$, there is no multiple reflection and the reflection of such a surface is identical to the reflection of a polished surface.

Theoretical works deal with a monochromatic plane wave and perfectly conducting surface. The latter condition precludes the need to consider the volumetric effect, which greatly simplifies analysis but, of course, places constraints on the model. Results obtained for an ideal conductor are usually modified by some approximate procedure for application to materials with finite productivity.

The topography of a surface that has been subjected to mechanical working is quite intricate. Both Beckmann and Davies assume that the surface is isotropic and formed by a continuous, stationary, random process. The function of two-dimensional distribution and autocorrelation coefficient are taken to be Gaussian. The mean quadratic deviation of the surface profile from the average line is designated by σ , while the correlation distance of profile points is designated by a . It is assumed that the shading of certain elements of the profile by others and multiple reflection between them are negligibly small.

Although Beckmann and Davies use identical formulations and solution methods for the diffraction problem, Davies employs two further simplifications. In the first place, he assumes that local perpendiculars (to the microfacets) coincide with the perpendicular to the average plane of the reflecting surface. This is true, however, only for those elements of the surface which have very small inclination. In the second place, his solutions are restricted to the marginal cases of very small and very large values of optical roughness. Both theories were subjected to critical analysis by theoretical calculations and comparison of results with experimental results [30]. It was determined that Davies' model has quite a limited sphere of application and Beckmann's model is more refined. Therefore, in what follows we will focus on it.

Basing himself on diffraction theory Beckmann obtained an expression that describes the spatial distribution of energy reflected from a perfect conductor for arbitrary values of the ratio σ/λ . We will give the expression for a reflected flux in the same form used in work [30]; the system of coordinates and angle designation are shown

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in Figure 11 below:

$$f(\psi, \zeta; \theta, \varphi) = f_c(\psi, \zeta; \theta, \varphi) F(u) + f_{nc}(\psi, \zeta; \theta, \varphi),$$

where

$$f_c(\zeta, \psi; \theta, \varphi) = \frac{\pi^2 \sigma^2}{\cos \psi \cos \theta} B(\theta, \varphi; \psi, \zeta) \times \exp \left[-G \left(\frac{\sigma}{\lambda}, \theta, \varphi \right) \right] \times \sum_{m=1}^{\infty} \frac{\left[G \left(\frac{\sigma}{\lambda}, \theta, \varphi \right) \right]^m}{m!} \exp \left[-\frac{\pi^2 \sigma^2}{m \lambda^2} h(\theta, \varphi; \psi, \zeta) \right]; \quad (7)$$

$$f_c(\psi, \zeta; \theta, \varphi) = \frac{\pi}{\Delta \omega_i \cos \psi} \exp \left[-\left(\frac{4\pi \sigma}{\lambda} \cos \psi \right)^2 \right]; \quad (8)$$

$$B(\theta, \varphi; \psi, \zeta) = \left[\frac{1 + \cos \theta \cos \psi + \sin \theta \sin \psi \cos(\zeta - \varphi)}{\cos \theta + \cos \psi} \right]^2;$$

$$h(\theta, \varphi; \psi, \zeta) = [\sin^2 \psi + \sin^2 \theta + 2 \sin \psi \sin \theta \cos(\zeta - \varphi)];$$

$$G \left(\frac{\sigma}{\lambda}, \theta, \varphi \right) = \left[2\pi \frac{\sigma}{\lambda} (\cos \theta + \cos \psi) \right]^2;$$

$$F(u) = U(\theta - \psi) U(\psi + \Delta \psi - \theta) U[\varphi - (\zeta + \pi)] U[\zeta + \pi + \Delta \zeta - \varphi];$$

$$U(x) = \begin{cases} 0 & x \leq 0; \\ 1 & x > 0; \end{cases} \quad \Delta \omega_i = \sin \psi \Delta \psi \Delta \zeta.$$

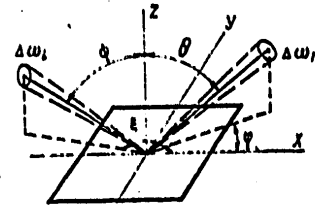


Figure 11. Angles of Incidence of Reflection

The symbol f is used to designate the two-directional coefficient of reflection* of a perfectly conducting material and the indexes c and nc represent the coherent and non-coherent components. The former is light reflected in mirror fashion at an angle equal to the angle of incidence and within the same space angle as incoming light; the latter is the light dispersed within the limits of a half-space. It should be kept in mind that a certain part of the diffusely scattered light is also propagated in the mirror direction, in addition to the light reflected in mirror fashion.

As equation (8) shows, the coherent component depends on the angle of incidence ψ , the optical roughness σ/λ , and the space angle $\Delta \omega_i$, which contains the incoming energy. For a sufficiently small angle $\Delta \omega_i$, changes in the magnitude of f_c according to $\Delta \omega_r$ for fixed ψ and σ/λ may be negligibly small.

The non-coherent component f_{nc} depends not only on the optical roughness and direction of arrival but also on the direction in which energy is reflected and the ratio of the correlation distance to the wavelength a/λ . The ratio σ/a is proportional to the mean quadratic inclination of elements of the rough surface.

* American investigators call the ratio of the intensity of light reflected in some direction θ, ϕ to the intensity of light arriving in direction ψ, ζ the two-directional coefficient of reflection.

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Figure 12 below shows the indicatrices of the non-coherent component in the case of light arriving at close to perpendicular ($\psi = 10$ degrees) calculated according to equation (7). The figure shows the ratio of

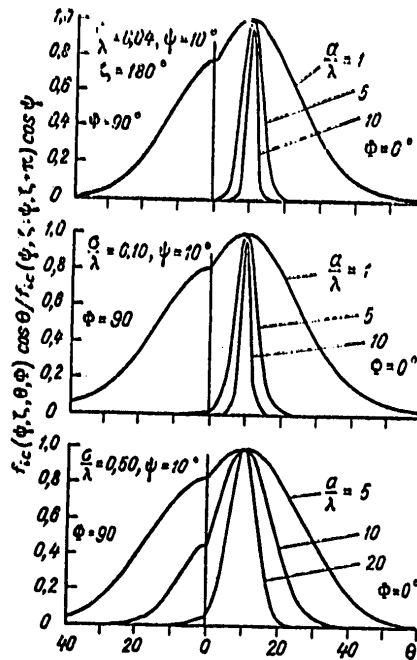


Figure 12. Indicatrixes of Light Dispersion Calculated According to Beckmann's Theory

the product of the coefficient of reflection (brightness) and the cosine of the angle of reflection [$f_{ic}(\psi, \zeta; \theta, \phi) \cos \theta$] to the value of the same quantity estimated in a mirror direction [$f_{ic}(\psi, \zeta; \theta, \phi) \cos \theta$]. This ratio makes it possible to estimate the quantity of dispersed light in any direction in fractions of the amount of light dispersed in a mirror direction. The right part of the figure gives values for the plane of incidence ($\phi = 0$ degrees) and the left part for the plane perpendicular to it ($\phi = 90$ degrees). The optical roughness values are 0.04, 0.10, and 0.50. Curves corresponding to different values of a/λ (from 1 to 20) are given in each individual figure.

The contribution of coherently reflected energy in the total reflected flux depends on the polar angle of incidence ψ and the magnitude of optical roughness σ/λ . The full contribution of the non-coherent component to the reflected flux can depend entirely on these same parameters. The parameter a/λ in the reflection of the non-coherent component f_{ic} may affect only its spatial distribution, not its full amount. The distributions shown in Figure 12 refer to the same amount of energy.

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It should be emphasized that an increase in the parameter a/λ (decrease in the mean quadratic inclination) results in the concentration of non-coherently reflected energy near the mirror direction and further that the magnitudes of optical roughness are not sufficient to characterize the distribution of reflected energy in space.

The law of preservation of energy may serve as the criterion for testing the correctness of the model under consideration and a significant deviation of the reflection coefficient from one will indicate that the model is not correct.* Such a calculation was made and the results are presented in Table 1 for different σ/λ and a/λ and for three angles of incidence. The numerator gives results for the Beckmann model and the denominator shows results for the Davies model. It is apparent that Beckmann's model is superior to the Davies model. Deviations from one do not exceed 0.02 and only in three cases reach values of 0.10, 0.15, and 0.518. But these cases come with comparatively large average inclination when shading may occur.

According to the Davies model a value of one is obtained only where $\sigma/\lambda < 0.04$. For greater values of optical roughness the coefficient of reflection exceeds one many times. It follows from this that the Davies model is applicable only to surfaces where the optical roughness is very small and light dispersion is insignificant. In other words, calculations by the Davies procedure can be done only applicable to extremely smooth surfaces.

Calculations on the Beckmann model for different ratios a/σ show that the coefficient of reflection is equal to one only in the domain $a/\sigma > 5$ and drops off sharply to zero for smaller values. Calculations using the Davies model produce worse results: The curve $p = f(a/\sigma)$ reaches one only when $a/\sigma \approx 30$.

Using the experimental data contained in Birkebak's dissertation [31] and referring to ground glass pieces coated with a thin layer of aluminum, the authors of the cited work calculated the quantity σ and a according to Beckmann's equation. They found that the quantity σ is somewhat smaller than shown in Birkebak's work, which used the Davies formula. As for the quantity a , it proved to vary for different wavelengths (See Table 2 below). The supposition was expressed that because the correlation distance is computed from experimental values of the hemispheric coefficient of reflection, if the latter for some reason was measured very inaccurately, this would have a marked effect on the magnitude of a also. Such an explanation cannot be considered exhaustive because it begins from the idea that the formula that relates the correlation distance to the reflection coefficient is unconditionally correct. It follows from Table 2 that where the wavelength changes

* This refers to the so-called "directed-hemispheric" coefficient of reflection: the light strikes on the perpendicular and is measured for the full hemisphere.

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Table 1. Coefficients of Reflection Computed for the Beckman and Davies Models

Angle of inci- dence	a/λ				
	1	5	10	50	100
$\sigma/\lambda = 0.01$					
0	$\frac{1.000}{0.999}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$
40	$\frac{0.998}{0.999}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$
80	$\frac{1.002}{1.000}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$	$\frac{1.000}{1.000}$
$\sigma/\lambda = 0.04$					
0	$\frac{1.000}{1.017}$	$\frac{1.000}{1.029}$	$\frac{1.000}{1.029}$	$\frac{1.000}{1.029}$	$\frac{1.000}{1.029}$
40	$\frac{0.9963}{0.995}$	$\frac{1.000}{1.010}$	$\frac{1.000}{1.010}$	$\frac{1.000}{1.010}$	$\frac{1.000}{1.011}$
80	$\frac{1.025}{1.015}$	$\frac{1.002}{1.001}$	$\frac{0.999}{1.000}$	$\frac{1.000}{1.000}$	$\frac{0.999}{1.000}$
$\sigma/\lambda = 0.10$					
0	$\frac{1.001}{1.705}$	$\frac{1.000}{1.782}$	$\frac{1.000}{1.785}$	$\frac{1.000}{1.785}$	$\frac{1.000}{1.785}$
40	$\frac{0.981}{1.226}$	$\frac{1.000}{1.319}$	$\frac{1.000}{1.322}$	$\frac{1.000}{1.323}$	$\frac{1.000}{1.325}$
80	$\frac{1.149}{1.094}$	$\frac{1.009}{1.009}$	$\frac{0.999}{1.000}$	$\frac{1.000}{1.001}$	$\frac{1.000}{1.001}$
$\sigma/\lambda = 0.20$					
0	$\frac{0.9846}{5.999}$	$\frac{1.000}{6.306}$	$\frac{1.000}{6.315}$	$\frac{1.000}{6.318}$	$\frac{1.000}{6.318}$
40	$\frac{0.9462}{3.344}$	$\frac{1.000}{3.719}$	$\frac{1.000}{3.728}$	$\frac{1.000}{3.731}$	$\frac{1.000}{3.731}$
80	$\frac{1.518}{1.389}$	$\frac{1.034}{1.048}$	$\frac{0.998}{1.013}$	$\frac{1.000}{1.017}$	$\frac{1.000}{1.017}$
$\sigma/\lambda = 0.50$					
	5	10	20	100	150
0	$\frac{1.000}{39.40}$	$\frac{1.000}{39.46}$	$\frac{1.000}{39.47}$	$\frac{1.000}{39.48}$	$\frac{1.000}{39.48}$
40	$\frac{0.990}{23.09}$	$\frac{1.000}{23.15}$	$\frac{1.000}{23.16}$	$\frac{1.000}{23.17}$	$\frac{1.000}{23.17}$
80	$\frac{1.102}{1.688}$	$\frac{0.981}{1.470}$	$\frac{0.980}{1.462}$	$\frac{1.000}{1.494}$	$\frac{1.000}{1.494}$

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Table 2

λ , MKM	σ/λ	a , MKM
1	0,566	3,88
2	0,283	5,76
4	0,141	8,71
6	0,094	11,53

by a factor of six the computed value of a changes by a factor of about 3. It is difficult to explain such changes by error in measuring the hemispheric coefficient of reflection. At the same time, for the smallest value of the correlation distance its ratio to the quantity σ is greater than five ($a/\sigma > 5$) and, therefore, is outside the domain where the calculated hemispheric reflection coefficient can differ substantially from one.

We should add to the above that rough surfaces produced by working a glass surface with a free abrasive and then applying a thin film of aluminum have all the features of a surface formed randomly. The distribution of heights and cut-off angles follows the normal law. Therefore, testing theories with experimental models is entirely valid and the discrepancies between calculated and experimental results should perhaps be explained not only by measurement error but also by the inadequacy of the theory.

Let us compare the data from calculations with results of experimental studies.

Formula (4), obtained experimentally, differs somewhat from theoretical formula (8), but it is easy to show that they coincide. In fact, the theory is dealing with mean quadratic deviation from the average profile line σ , whereas formula (4) gives the quantity h , which should be taken as the mean quadratic height of the profile. The quantity σ is related to the quantity R_a by the relation $R_a = 0.8\sigma$ [35]. At the same time, according to [36] $R_z \approx 5R_a \approx 4\sigma$. If we take $R_z = h$, then there is full correspondence between formulas (4) and (8).

Continuing, the calculated indicatrices of diffusely reflected light for angles of incidence of the light which are not too large coincide with experimental ones, while for large angles the theory predicts a shift of the diffuse maximum toward larger angles, which is in fact observed.

In the experimental and theoretical works considered it was assumed that a rough surface is formed by a random process characterized by

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Gaussian distribution with parameters σ and a . In reality it is possible that the totality of roughnesses will be a composite of several distributions. Assumptions of this type were expressed in [37, 38]. Beckmann conducted a theoretical investigation of the question [39]. He considered reflection from a complex surface and found that small structural components make a marked contribution to the total dispersion by a rough surface. Work [40] demonstrated experimentally the effect of the secondary structure of the rough surface on the distribution of light dispersed by it. We are not going into greater detail in this matter and will limit ourselves to these references, because this is quite a complex issue and there is still very little experimental material.

Let us summarize at this point. The properties of a rough surface have been studied primarily for flat pieces worked by a free abrasive. And although the planar models studied are fairly simple within the vast class of surfaces, the results obtained represent a significant advance in solving the problem of "interaction between magnetic emission and a rough surface." As the works we have reviewed show, the optical properties of a rough surface are determined by the ratio between the wavelength of incoming emission and the dimensions of the rough places: the mean quadratic height h and the mean quadratic inclination of the reflecting areas h/a . The intensity of the mirror component of the reflected flux, and therefore also the diffuse component, depend on h ; the spatial distribution of the diffuse component depends on h/a . The dependence of the intensity of the diffuse component is greatly simplified for very smooth surfaces: the full amount of diffusely scattered light is proportional to the square of optical roughness:

$$\left(\frac{h}{\lambda} \cos \psi\right)^2.$$

Thus, investigation of light reflected by a rough surface in mirror fashion and diffusely makes it possible to obtain very important information about the properties of the surface itself. Let us consider how the rules we have found are used to find the quantitative characteristics of the rough surface.

Determination of the Parameters of a Rough Surface

The important characteristics of a rough surface are the mean quadratic height of the microirregularities and the mean quadratic inclination of microfacets. As was shown above, the energetics of light reflected by the surface and its spatial distribution depend on them. Let us consider methods and procedures of determining these parameters based on the rules set forth earlier.

To establish a general background let us recall the techniques and instruments which already exist and are used to estimate rough surfaces. These are the profilographs, profile meters, double microscopes, and microinterferometers. The last two can produce certain results only for study of a surface with parallel traces (from abrasive working)

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or with singular parapins. The profilograph can write a profilogram for a small segment of the surface and by further processing it is possible to find the average height R_z for this segment. There are tables which make it possible to determine the quantity R_a for a known quantity R_z .

Photometric techniques are also known. For example, [32] suggests a method of determining the average height of roughness by comparison with test pieces in which this parameter has been obtained by two methods. Kartashev's monograph contains a description of many instruments and techniques [33].

The mirror component technique. The rule expressed quantitatively by formula (4) can be used to determine the mean quadratic height of micro-irregularities. Taking the logarithm of this expression we obtain

$$\ln I_s = \ln \bar{p} + \ln I_0 - \pi \frac{h^2}{\lambda^2} \cos^2 \psi. \quad (9)$$

Whereas $\bar{p}$ in a certain range of angles maintains a constant value, (9) can be represented graphically in the form of a straight line laid according to $\cos^2 \psi$ on the X axis and $\ln I_s$ on the Y axis. The tangent of the angle of inclination of this line is

$$\operatorname{tg} \alpha = -\pi \frac{h^2}{\lambda^2}.$$

To find the quantity h it is necessary to measure the mirror components I_{s1} and I_{s2} for a selected wavelength λ and angles of incidence ψ_1 and ψ_2 . Then it is possible to receive the formula for computing h from two equations of type (9):

$$h = \frac{\lambda}{\pi} \sqrt{\frac{\ln I_{s1} - \ln I_{s2}}{\cos^2 \psi_2 - \cos^2 \psi_1}}. \quad (10)$$

As is apparent from (10), the precision of measurement of h depends on the precision of measurement of the mirror component and the angle of incidence of light. Where the measuring instrument and receiver are chosen correctly and the signal is large enough, the largest possible relative error for the numerator of the fraction under the square root sign in formula (10) may be no more than 0.5 percent. Most errors should be expected from the denominator of the fraction; for angles $\psi < 40$ degrees it is 0.5 percent and where $\psi > 80$ degrees it may reach 10-15 percent [34].

Values of h corresponding to different rough surfaces are given in Table 3 to characterize the technique. It should be noted that the mirror component was measured on a goniophotometric device with a resolution of a few angular minutes.

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Table 3

h, мкм							
Абразивы а)	Сталь б)	Дюраль в)	Кремний г)	Кварцевое стекло е)	Стекло К8 ф)	Сн- талл г)	Стекло ТФ5 з)
M3	0,11		0,32				
M5	0,29		0,50				
M7				0,92	1,32	1,13	1,59
M14		1,34		1,49	1,89	1,54	2,47
M40				2,5	3,16	3,2	4,2
M3		5,2					
M6		9,0		5,8	6,82	7,1	10,1

Table 3.

Key: (a) Abrasives; (e) Quartz Glass;
 (b) Steel; (f) K8 Glass;
 (c) Duralium; (g) Ceramic Glass;
 (d) Silicon (h) TF5 Glass.

The range of rough surfaces indicated in the table covers samples from classes of roughness six to 12. Some of the figures given are comparable with figures obtained by profilometer. It turned out that h is very close to R_z .

Smoother surfaces are classified as polished, and for them determination of h cannot be done by formula (10) because measurement error will be commensurate with the quantity being measured. In other words, the mirror component method is not suitable; it is not sensitive enough for the study of polished surfaces.

Work [24] was cited above. In it the quantity σ was determined by the mirror component technique. In this case the smallest magnitude of optical roughness σ/λ was about 0.003. It should be kept in mind here that measurements of the coefficient of mirror reflection were done by means of an infrared spectrophotometer and the wavelengths employed were an order greater than the wavelengths of the visible spectrum. According to the authors' evaluation, the precision of measurement was about 0.1 percent. We will see later that the amount of dispersed light in supersmooth mirrors is less and therefore the sphere of application of this technique is limited to the cited values of precision.

Work [20] measured the indicatrices of the reverse reflection of ground glass samples using the formula given in [39] and found the values for mean quadratic inclination m and correlation distance a shown in Table 4 below. The values for inclination of microfacets match the results of

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Table 4

σ, μ	Inclination, m		α, μ
	Radians	Degrees	
0.27	0.189	11	2.05
2.33	0.247	14	13.2
4.37	0.273	15.5	22.6

work [45] well. This work investigated the cut-off angles on the surface of optical glass which was worked with grinding powder of different grain sizes. According to the data in [45], the average cut-off angle was approximately 150 degrees, and therefore the average angle of inclination of microfacets was about 15 degrees.

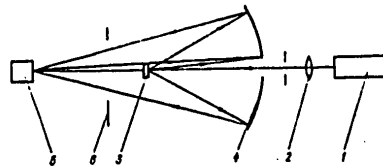
The diffuse component technique. I. In developing a technique for determining the parameters of a polished surface, Hodgkinson [41] began from the idea that in addition to the beam the receiving device is struck by a certain amount of diffusely scattered light which can be taken into account if we use the expression

$$p/p_0 = e^{-\left(\frac{4\pi\sigma}{\lambda}\right)^2} + \left[1 - e^{-\left(\frac{4\pi\sigma}{\lambda}\right)^2}\right] \left[1 - e^{-\left(\frac{\pi\sigma\alpha}{m\lambda}\right)^2}\right]. \quad (11)$$

In this p is the coefficient of reflection being measured; p_0 is the coefficient of reflection of an ideal mirror; m is the mean quadratic inclination of the microfacets that disperse the light within the ranges of the angle 2α . The first term in expression (11) represents the intensity of the mirror component of the reflected flux, while the second is the intensity of the diffuse component received by the receiving device simultaneously with the mirror component. The binomial in the first parentheses expresses the full quantity of diffusely scattered light, while the quantity in the second parentheses is that part which is dispersed within the limits of the angle 2α .

Measurements of dispersed light were made by means of a device whose optical diagram is represented in Figure 13 [41]. The light beam from

Figure 13. Optical Diagram of A Device To Measure Dispersed Light



gas laser 1 (He-Ne) passed through lens 2 and was collected by it on measured test piece 3 on a spot 0.3 millimeters in diameter. As we

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As we can see from the diagram, the light reflected in mirror fashion departed back through the aperture of the spherical mirror, while the dispersed light struck spherical, concave mirror 4 and was collected in a plane conjugate with the test piece at photomultiplier 5. The aperture of the dispersed beam could be changed within the range 0.035-0.35 of a radian by means of iris diaphragm 6. Thus, only dispersed light changed for different openings of the diaphragm.

The curve of the relationship $I_d = f(a)$ represented in Figure 14 below shows that as the aperture was enlarged the intensity of dispersed light grew sharply at first, then the curve became more gentle and at a certain value of a reached a value I_d , which the author takes to be maximum.

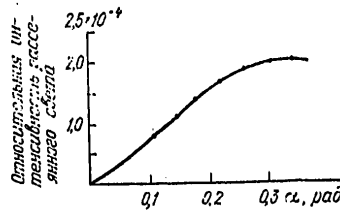


Figure 14. Dependence of the Intensity of Dispersed on the Angle of Dispersion

The intensity of the diffuse component, normed for incoming light, may be written as follows:

$$I_d \approx \left(\frac{4\pi\sigma}{\lambda}\right)^2 \left[1 - e^{-2\left(\frac{\pi m a}{\lambda}\right)^2}\right].$$

Considering that the angular density of dispersed light outside angle $a_{\max}$ is very small, the author neglects the second term in (11); then $I_d \approx (4\pi\sigma/\lambda)^2$, from which σ is found. As for the mean quadratic inclination m , its magnitude is determined by matching experimental points $I_d(a)$ to a function of the type $[1 - \exp(ba^2)]$ where b is a constant.

The test pieces studied were glass backed by plates of melted quartz 5×5 millimeters in size, carefully polished and all coated at the same time with a layer of silver. The results of measurement of the quantities σ and m are given in Table 5; this table also shows the time of additional polishing of the samples.

Our attention is drawn to the fact that the quantity σ was several Angstroms; it was especially small for the last sample (just 2.3 Angstroms, that is, less than the dimensions of a silicon dioxide molecule).

To confirm these results, in parentheses the author gives findings for the same test pieces obtained by the technique of multiple ray

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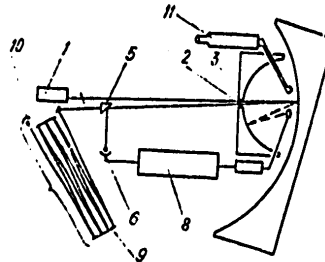
Table 5

Time of Additional Polishing, minutes	σ , Å	$m \times 10^3$, radians
15	9.7 (7.6)	1.25 (0.32)
45	7.3	1.12
75	6.8	0.78
120	5.6	0.59
330	2.3 (2.4)	0.38 (0.21)

interference (the method of strips of equal chromatic order). It should be recalled that σ is the mean quadratic deviation of profile points from the average line, whereas the true mean quadratic height of roughness is approximately four times larger.

II. Bennet, the author of a number of studies of rough surfaces, has proposed two modifications of the instrument to estimate the dimensions of roughness of reflecting mirrors [46]. Figure 15 gives the optical diagram of one of them. A gas laser 1 provides the source of light.

Figure 15. Diagram of an Instrument To Determine the Average Height of Roughness



The light beam from it passes through opening 2 in hemisphere 3, whose internal surface is a mirror. The beam, reflected in mirror fashion by test piece 4, departs back through the same opening and is deflected by prism 5 to pyroelectric receiver 6. The light dispersed by the test piece strikes the mirror surface of hemisphere 3 and is collected on the surface of a second pyroelectric receiver 7 because its center is located at a point conjugate with the center from which the light is dispersed. The receiver window is made from a material with a low refraction index (BaF) and has a dome shape, while the surface itself is darkened.

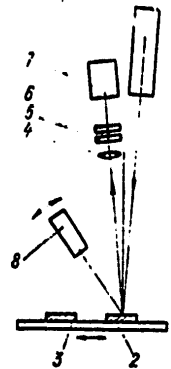
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Signals from both receivers are fed to electronic unit 8, which records the ratio p_d/p_g (p_d is the coefficient of diffuse reflection and p_g is the coefficient of mirror reflection of the mirror being tested).

The test piece is set correctly relative to the instrument by means of additional devices. The piece must be placed so that the beam reflected in mirror fashion departs through opening 2 and strikes receiver 6 and so that receiver 7 is located at the point where the dispersed beams reflected from hemisphere 3 converge. The former is achieved by means of a special device consisting of a system of mirrors 9 and a thermistor detector 10; the latter condition is monitored visually by means of an optical device with fiberoptics 11.

III. The work by Hildebrand, Gordon, and Allen [42] describes an instrument used by the authors to measure the values of σ for mirrors by the relative method. Figure 16 diagrams the device. Gas laser 1

Figure 16. Diagram of A Device To Determine the Quantity σ



provides the source of illumination. It illuminates test piece 2 and comparison piece 3 alternately at an angle of eight degrees. The light reflected in mirror fashion passes through objective 4 and glass screens 5 and 6, striking semiconductor photo cell 7 whose output signal is amplified. The light that is diffusely reflected is recorded in the eight degree aperture of photomultiplier 8 every five degrees in the angular range 20-75 degrees. The output signals of detectors 7 and 8 go to the input of an analog divider and the ratio between them is recorded on the diagram tape of the self-recorder as a function of the angle of reflection θ .

We know from the theory in [28] that for normal distribution of heights of irregularities this ratio is

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$$\omega(\theta) = \frac{I(\theta)}{I(\theta_0)} = 2\pi^2 \frac{a_0^2}{\lambda^2} (\cos \theta + 1)^2 \sin \theta \times \exp \times \left[-\left(\frac{\pi a \sin \theta}{\lambda} \right)^2 \right] \exp \left(\frac{4\pi a^2}{\lambda^2} \right), \quad (12)$$

where a is the correlation distance.

The determination of σ_0 for the test piece is done by comparing it with a piece whose mean quadratic deviation σ_a is known. The ratio of two expressions of type (12) has the form

$$\Omega(\theta) = \frac{\omega_0(\theta)}{\omega_a(\theta)} = \left(\frac{a_0 a_a}{a_a^2} \right)^2 \exp \left[(4\pi)^2 \frac{a_0^2 - a_a^2}{\lambda^2} \right] \times \exp \left[-\left(\frac{\pi \sin \theta}{\lambda} \right)^2 (a_0^2 - a_a^2) \right], \quad (13)$$

where the indexes 0 and a refer to the test piece and comparison piece respectively. Assuming that

$$a_0 \approx a_a, \text{ and } \frac{a_0^2 - a_a^2}{\lambda^2} \ll 1,$$

a very simple expression can be obtained from (13) for finding σ_0

$$a_0 = a_a \sqrt{\Omega(\theta)}.$$

The authors point out that the values of σ_0 obtained for different angles θ are different, even though in theory this should not be because relationship (13) does not depend on θ . Therefore, when determining σ_0 they used an average value $\bar{\Omega}(\theta)$ equal to

$$\bar{\Omega}(\theta) = \sum_{i=1}^N \frac{\Omega_i(\theta)}{N}.$$

The results of measurement were compared with findings obtained on a device designed to measure the mirror coefficient of reflection [26]. A polished quartz plate with an aluminum layer of $\sigma = 10\text{\AA}$ applied in a vacuum was used as a comparison piece. Copper mirrors served as test pieces.

IV. The method presented below [43, 44] is based on the use of relation (9), which may be rewritten as follows

$$\frac{I_d}{I_0} = p_d = p \frac{\pi^2 \lambda^2}{\lambda^2} \cos^2 \psi. \quad (14)$$

The general coefficient of reflection p is given here instead of the effective coefficient $\bar{p}$ because we are now dealing with a polished surface. From (14) we obtain the formula

$$h = \frac{\lambda}{\pi \cos \psi} \sqrt{\frac{p_d}{p}}.$$

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from which it follows that to determine the mean quadratic height of roughness of a polished surface it is sufficient to measure the full flux reflected by the surface and the flux reflected diffusely.

Figure 17 gives a diagram of the measuring device. The light beam from gas laser 1 (He-Ne) passes through an opening in globe 2 and strikes the polished test piece 3. The light reflected in mirror fashion leaves the globe through opening 4 and is extinguished in trap 5. At the same time the diffusely reflected light creates a certain illumination on the walls of the globe whose level is recorded by means of a detection and measuring unit consisting of photo multiplier 6 and measurement device 7. Then opening 4 is closed by screen 8. Now the illumination of the walls of the globe is a result of the entire flux reflected from the test piece. The new level of illumination is recorded with the same receiving and recording device [44].

The magnitudes of the signals may differ by several orders and light filters that reduce the greatest flux an appropriate number of times are used to be able to measure them at the same level of sensitivity on the receiving and measuring instrument. By changing the diameter of the output opening it is possible to study the distribution of dispersed light near the mirror-reflected beam. Figure 18 represents a series of curves of dispersion of polished metallic surfaces with different classes of roughness. The amount of diffusely dispersed light

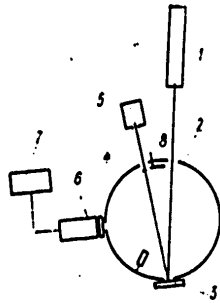


Figure 17. Diagram of a Device with a Photometric Globe for Determining the Quantity h

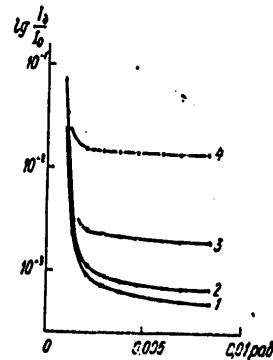


Figure 18. Dispersion of Light by Polished Metal Surfaces (numbers on the curves correspond to numbers in Table 6.)

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reduced to the full reflected flux is laid out on the Y axis and the half angle of the output opening in minutes is put on the X axis. As the diameter of the opening increases, more dispersed lights escapes from the photometric globe. The steepness of the curve of dispersed light is greatest for small diameters, but as the diameter of the diaphragm increases the steepness decreases and when the opening is opened to an angle of approximately four degrees (half angle of 120 minutes), the curve becomes almost parallel to the X axis.

These findings permit not only a comparative estimate of the quality of mirrors studied, but also a quantitative determination of their parameters. Table 6 below gives the values of the normed magnitude of dispersed flux and mean quadratic height of roughness of the mirror calculated from these data. The first three mirrors are quartz backings characterized by different degrees of polishing and coated with a fine layer of aluminum. The last two are metallic mirrors.

Номер зеркала (a)	Отношение диффузно отраженного потока ко всему отраженному потоку (b)	Среднеквадратическая высота шероховатости, Å (c)
1	$8,6 \cdot 10^{-4}$	58
2	$9,2 \cdot 10^{-4}$	64
3	$35,0 \cdot 10^{-4}$	118
4	$160,9 \cdot 10^{-4}$	252
5	$383,7 \cdot 10^{-4}$	392

Table 6.

Key: (a) Mirror Number;
 (b) Ratio of Diffusely Reflected Flux to Full Reflected Flux;
 (c) Mean Quadratic Height of Roughness, Å.

According to existing State All-Union Standards [10], the test piece No 5 should be classified as roughness 14, while all the earlier ones are higher classes. It is noteworthy that the amount of dispersed light for the last piece is almost four percent of the total reflected flux, but as we move to smoother test pieces it drops to hundredths of a percentage point.

All the techniques considered for determining the dimensions of roughness of polished, non-transparent surfaces are based on measuring the diffuse component of a reflected flux whose intensity is related in some certain way to the height of roughness. However, the smoother a mirror is, the less light it will scatter, and therefore, the greater the effect of outside sources of dispersed light will be. There is no question that mirrors with average roughness of less than 0.015λ should be tested in special conditions that preclude these sources.

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HIGH-ENERGY DEVICES, OPTICS AND PHOTOGRAPHY

NEW STATE STANDARDS FOR TEST GLASSES, FILM REELS

Leningrad OPTIKO-MEKHANICHESKAYA PROMYSHLENNOST' in Russian No 1,
1979 p 57

[Article: "New State Standards"]

[Text] GOST [State All-Union Standard] 2716-76. "Test Glasses for Testing the Radii of the Spherical Surfaces of Optical Parts. Technical Specifications."

On 1 July 1977 GOST 2786-76 was put in effect. It applies to test glasses designed to test the radii of the spherical and flat surfaces of optical parts by the interference method.

The following types of test glasses are manufactured:

1. Basic test glasses (OPS) for testing the surfaces of test glasses;
2. Testing test glasses (KPS) for testing the surfaces of working test glasses;
3. Working test glasses (RPS) for testing the surfaces of parts.

The shape and dimensions of the basic glasses are given in lines 1-6 and in Tables 1 and 2 of the standard. The shape and dimensions of the testing and working glasses depending on the diameter and radius of the surface being tested are given in drawings 7 and 8 and in Table 2.

Basic test glasses of all radii are manufactured in pairs consisting of a convex glass and a concave glass.

The testing test glasses must have a curve that matches the curve of the surfaces being tested, while the working test glasses must have a curve that is the inverse of the curve of the parts being tested.

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The GOST contains the following sections: types and basic dimensions; technical requirements; rules for acceptance; monitoring techniques; marking, packing, transporting, and storing; the manufacturer's guarantee.

The appendix gives a sample factory document for a glass used to test the radii of the spherical surfaces of optical parts.

GOST 18373-77. "Reels for 8-Millimeter and Type S8-Millimeter Movie Film. Technical Specifications."

GOST 18373-77 was put in effect on 1 January 1978 to replace GOST 18373-73. The new standard refines the types and basic parameters of reels and increases requirements for their technical level and quality. It does not apply to special reels designed for automatic film loading or built into the film projector.

The standard corresponds to recommendation R 892-1968 of the International Organization for Standards and international standard MS3639-1975 in the part referring to basic connecting dimensions.

The following type-sizes of reels are manufactured:

Designation of Type-Size	Capacity, Meters	Area of Use
8-15	15	For 8-Milli- meter Movie Films
8-30	30	
8-60	60	
8-120	130	
8S-15	15	For Type S 8- Millimeter Film
8S-30	30	
8S-60	60	
8S-120	120	
8S-180	180	
8S-240	240	
8S-360	360	

The dimensions of the reels are given in the drawing and in Tables 2 and 3.

The standard contains the following sections: types and basic dimensions; technical requirements; rules of acceptance; testing methods; marking, packing, transportation, and storage; the manufacturer's guarantee.

The appendix gives definitions of certain terms used in the standard.

GOST 22059-76. "Movie Camera Reels for Photographing on Double 8-Millimeter Film. Technical Specifications."

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On 1 July 1977 GOST 22059-76 was put into effect. It applies to reels used in movie cameras to film with double 8-millimeter (2 x 8 millimeter) film according to GOST 8761-75. The standard corresponds to international standard R1020-1969 of the International Organization for Standards with respect to the basic connecting dimensions.

Two types of reels are manufactured:

- A. With discs that have different loading holes (three and four notches);
- B. With discs that have identical loading holes (three notches).

Note. Reels of type B are designed for cameras that have a blocking system that prevents double exposures.

The basic dimensions of the reels are given in drawing 1. The standard contains the following sections: types and basic dimensions; technical requirements; rules of acceptance; testing methods; marking, packing, transportation and storage; manufacturer's guarantees.

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HIGH-ENERGY DEVICES, OPTICS AND PHOTOGRAPHY

NEW OPTICAL DEVICES, PROCEDURES PATENTED

Leningrad OPTIKO-MEKHANICHESKAYA PROMYSHLENNOST' in Russian No 1, 1979
pp 57-58

[Article: "New Author's Certificates"]

[Text] Microscope Eyepiece — L. N. Andreyev and O. V. Bagdasarova,
Author's Certificat No 57001, BYUL. IZOB. 1977, No 31, p 161.

A microscope eyepiece containing a positive collective and positive eye component between which a double-glued positive lens is placed, distinguished by the fact that the collective, in order to improve the correction for chromatism and enlarge the field of vision, is made in the form of a double-glued negative and positive lens; the difference in the indexes of refraction of the materials of the negative and positive lenses does not exceed 0.03 and the difference between the coefficients of average dispersion is not greater than 20.

Modulator — V. A. Zhoglikov and B. V. Kiyashko, Author's Certificate No 570003, BYUL. IZOB. 1977, No 31, p 162.

A modulator for an optical spectrum analyzer, containing two polarizers and a prism of double-refracting crystal mounted between them, distinguished by the fact that an additional prism of double-refracting crystal is mounted between one of the polarizers and the primary prism in order to linearize the frequency axis in the frequency range close to zero.

Interference Technique for Absolute Measurement of the Indexes of Refraction of Plane-Parallel Plates — A. D. Briks and Ye. A. Volkova, Author's Certificate No 570768, BYUL. IZOB. 1977, No 32, p 106.

An interference procedure for absolute measurement of the indexes of refraction of plane-parallel plates with semitranslucent coating, based on measurement of the thickness of a test piece and the order of interference, distinguished by the fact that, for the purpose of improving precision, these operations are done with at least two test pieces of different thicknesses made of the same material and the measured values are used to determine the index of refraction of the material.

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Refractometric Cell — B. I. Molochnikov, I. S. Vasil'yeva, and M. V. Leykin, Author's Certificate No 570822, BYUL. IZOB. 1977, No 32, p 117.

A refractometric cell containing at least two prismatic cavities with substances being compared confined by outer plates, one of which has a reflecting coating, and inner plates set at an angle to the outer ones, distinguished by the fact that, to minimize the volume of the cell while simultaneously increasing its angular sensitivity, a reflecting coating is also put on the second outer plate and each reflecting coating has openings for beams of light to enter and depart, with the centers of the openings set at an identical height in relation to the refracting rib of the cell and on different sides from a plane perpendicular to this rib and passing through its midpoint.

Reproduction Objective — Volosov, M. G. Shpyakin, L. G. Kochetova, and A. M. Rozenberg, Author's Certificate No 570865, BYUL. IZOB. 1977, No 32, p 126.

A reproduction objective containing eight components and a diaphragm set between the fourth and fifth components, with the first component made in the form of a negative double-glued meniscus, the third and fourth as double-glued and single meniscuses respectively, and all the meniscuses concave with respect to the objective, distinguished by the fact that, in order to enlarge the output numerical aperture and improve the quality of the image, the components placed between the diaphragm are, in order, a single meniscus and two double-glued meniscuses turned concave with respect to the image, and a convex-flat lens.

Film Projector — A. A. Borisyuk, Author's Certificate No 570869, BYUL. IZOB. 1977, No 32, p 127.

A film projector containing a light source with a condenser, film drive mechanism, film channel, and shutter, for example of the obturator type, projection system, and screen, distinguished by the fact that, to provide a possibility of viewing negatives in a positive image, it has an objective between the shutter and the projection system and an inclined circular mirror optically linked through a flat mirror with an additional source of light that has a condenser and slotted mirror mask in front of which an additional transparent screen with a current-conducting coating made of semiconductor material is installed, connected to a power source through a switching device that is kinematically linked to the film drive mechanism and shutter.

Anamorphic Objective with Variable Focusing Distance — B. M. Ardashnikov, A. B. Agurok, T. M. Vil'ner, and G. V. Soboleva, Author's Certificate No 565271, BYUL. IZOB. 1977, No 26, p 97.

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objective with variable focusing distance, containing an afocal anamorphic adapter that includes a negative glued lens and a positive glued lens and a spherical objective placed behind the adapter with a variable focusing distance, containing four components, the first of which is in the form of a positive glued lens, while the second and third are mounted in a way that permits shifting along the optical axis, distinguished by the fact that, to improve the quality of the image at high luminosity, a positive cylindrical lens is mounted in front of the negative glued lens of the adapter, a single positive lens is placed behind the positive glued lens of the first component of the spherical objective, and the fourth component of the spherical objective is made in the form of a single positive lens, a positive meniscus and a negative meniscus turned concave with respect to the image, a negative glued lens, and a single positive lens.

Method for Checking the Shape of Convex Hyperbolic Surface of an Optical Part — D. T. Puryayev and V. A. Gorshkov, Author's Certificate, No 571698, BYUL. IZOBR. 1977, No 33, p 121.

A method of checking the shape of a convex hyperbolic surface of an optical part, in which a point light source illuminates the surface being checked and the shade picture obtained when rays are reflected from the checked surface is observed, distinguished by the fact that, in order to increase the precision of measurement, an additional lens is set on the optical part on the side of the surface that is not being checked; with the optical parts being checked this lens forms a flat-convex system and the total thickness d of the resulting system is related to the radius of curve r_0 at the apex, eccentricity e of the surface being checked, and the index of refraction n of the system by the relation

$$d = \frac{r_0}{8} \left(4 - \frac{e^2 - 1}{n^2 - 1} \right),$$

while the point light source is set at distance S from the flat surface of the resulting system, defined by the relation

$$S = \frac{r_0}{8n} \left(\frac{e^2 - 1}{n^2 - 1} \right).$$

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Aeronautical and Space

USSR

UDC 629.78.064.001

POWER SYSTEMS OF AEROSPACE DEVICES

Moscow ENERGETICHESKIYE SISTEMY KISMICHESKIKH APPARATOV in Russian 2nd edition, revised and supplemented, Izd. Mashinostroyeniye, 1979 320 pp

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.149 by T. A. Ye.]

KULANDIN, A. A., TIMASHEV, S. V. and IVANOV, V. P.

[Text] The book contains the following chapters: 1. General information on energy systems of aerospace vehicles. 2. Radioisotope sources of thermal energy. 3. Nuclear fission reactors. 4. Devices for liberating heat in space. 5. Thermoelectric converters and energy devices. 6. Thermoemission converters and energy devices. 7. Energy devices based on mechanical heat converters. 8. Electrochemical converters and energy devices. 9. Photoelectric converters, solar batteries and energy devices employing them. 10. Electrothermal jet engines. 11. Electromagnetic jet engines. 12. Electrostatic and Hall-ion jet engines. 13. Energy systems of aerospace vehicles as the synthesis of basic elements of on-board power engineering. The book is intended for technical and engineering workers engaged in problems of aerospace power engineering. It may be useful to students and graduate students in vuzes of various specializations.

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Navigation and Guidance Systems

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UDC 629.78.076.6

USING INFLUENCE FACTORS TO CONTROL FLIGHTCRAFT VELOCITY

Moscow TRUDY MOSKOVSKOGO VYSSHEGO TEKHNIЧЕСКОГО UCHILISHCHA IMENI N. E. BAUMANA [Proceedings of Moscow Higher Technical Academy imeni N. E. Bauman] in Russian No 265, 1978 pp 53-63

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 10, 1978 Abstract No 10.41.93]

DEMENKOV, N. P.

[Text] The author discusses problems associated with using influence factors to control the velocity of a flightcraft that is maneuvered in the longitudinal (vertical) plane by changing the banking angle while holding the trim angle of attack constant. Figures 2; references 8.

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Fluid Mechanics

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UDC 629.78.015:533.6.011.55

ON BRANCHING OF THE LIMITING SHOCK LAYER IN HYPERSONIC AERODYNAMICS

Irkutsk ASIMPTOTICHESKIYE METODY V TEORII SISTEM [Asymptotic Methods in the Theory of Systems] in Russian 1978, pp 79-87

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.112]

NARITSA, V. S.

[Text] A two-dimensional steady-state problem of hypersonic flow of ideal gas around bodies is investigated where the Mach number tends toward infinity and the ratio of specific heats approaches unity. Flow is concentrated in an infinitely thin layer with infinitely great density. This shock layer may be detached from the body and become free. In bodies with projections, more complex forms of limiting flow are possible. Several questions on the study of the limiting shock layer based on the region of constant pressure have been dealt with before. In this study, primary attention is given to construction of a model of branching of a shock layer with formation of two constant pressure zones. A two-parameter solution is derived for both smooth branching and for non-smooth branching. As illustrations are considered flows about a straight circular cylinder and a sphere. It is noted that three parameters on which the shape of the shock layer depends after the branching point can be put in correspondence with three geometric parameters; if it was free before branching, the correspondence is unambiguous. Figures 3; references 4.

USSR

UDC 629.78.015:532.526

APPROXIMATE ANALYSIS OF THE EFFECT OF A LONGITUDINAL PRESSURE GRADIENT ON CRITICAL PARAMETERS OF DISPLACEMENT OF A TURBULENT BOUNDARY LAYER ON PERMEABLE SURFACES

Kiev PRIKLADNAYA AERODINAMIKA in Russian No 4, 1978 pp 7-13

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.125]

YERMAKOV, A. L. and YANOVSKIY, L. S.

[Text] Based on the theory of limiting relationships of Kutateladze and Leont'yev, analysis is made of the effect of negative and positive longitudinal pressure gradients on critical parameters of displacement of a turbulent boundary layer on a permeable wall. An interferometric method is used with high accuracy to derive critical parameters of displacement of a

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diffusion boundary layer, which are successfully correlated by simple equations. Practical recommendations are made for engineering calculations. Figures 2; references 5.

USSR

UDC 629.78.015:532.526

DETACHMENT OF A TURBULENT BOUNDARY LAYER ON SURFACES WITH CORNERS

Kiev PRIKLADNAYA AERODINAMIKA in Russian No 4, 1978 pp 13-19

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.114]

TSIPENKO, V. G.

[Text] Results are cited of computer calculations of turbulent detached flows in a supersonic stream in front of a curved wall by the two-parameter method of integral equations. Integral properties of viscous flows are represented by Stuartson-Cohen-Reshotko profiles as applied to turbulent flows. An equation of energy of pulsating motions is used as a condition of closure for the turbulence effect of viscosity. Results of calculations done in a wide range of measurements of Reynolds' and Mach numbers are compared with experimental data. Figures 3; references 5.

USSR

UDC 629.78.015:533.6

EXPERIMENTAL STUDY OF A SEMI-BOUNDED JET ON A CYLINDER IN A COUNTER FLOW

Kiev PRIKLADNAYA AERODINAMIKA in Russian No 4, 1978 pp 43-54

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.92]

LAZNYUK, P. S. and SOTNIKOV, D. A.

[Text] Results are cited of an experimental study of the varied velocity and section of a jet and rate of external flow for various relationships of nozzle and cylinder diameter. Data are obtained on parameters of the initial and basic sections of jet flow, on change of maximum velocity, width of the displacement zone and profile of velocities. Constants are defined for turbulence for the initial and basic sections of the jet. Figures 9; table 1; references 15.

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UDC 629.78.015:533.6.015.04

INVESTIGATION OF DETACHED FLOW AROUND A SYMMETRIC HYDROFOIL IN AN INCOMPRESSIBLE LIQUID

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA
[Scientific Annals of Central Aerohydrodynamics Institute] in Russian Vol
9 No 6, 1978 pp 1-8

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.105]

BRUTYAN, M. A.

[Text] An examination is made the problem of the effect of viscosity on symmetric flow around a hydrofoil in the presence of turbulent diffuser boundary layer separation. In calculating the characteristics of the boundary layer by the integral method in the region of intense interaction, a process of successive approximations is constructed in which laws are given for the change in friction on the foil surface and velocity on the wake axis, and the pressure distribution at the outside of the boundary layer is considered as a dependent variable. Results of calculations agree satisfactorily with experimental data. Figures 4; references 18.

USSR

UDC 629.78.018.1

THE EFFECT OF PERMEABLE BOUNDARIES OF A TRANSSONIC STREAM ON FLOW AROUND BODIES OF REVOLUTION

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA
in Russian Vol 9 No 6, 1978 pp 17-27

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.124]

TRET'YAKOVA, I. V. and FONAREV, A. S.

[Text] The problem of flow around bodies of revolution in an unbounded transonic gas stream and in a flow with walls having an assigned coefficient of permeability is examined using the numerical method of relaxation. Numerical solutions are derived for flow around various bodies of revolution in subsonic and supersonic unperturbed streams near the speed of sound. Analysis is done on the effect of permeable walls in the working section of the tunnel in the case of control of gas parameters near the wall, both due to generation of variable pressure along the length of the outer chamber and by changing the coefficient of permeability along the tunnel. Figures 7; tables 2; references 10.

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UDC 629.78.015:533.6

CALCULATION OF TRANSSONIC FLOW AROUND AXISYMMETRIC PLANE BODIES, ALLOWING FOR THE EFFECT OF A PERFORATED WALL IN THE WIND TUNNEL AND A TAIL SUPPORT HOLDER

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA [Scientific Annals of Central Aerohydrodynamics Institute] in Russian Vol 9 No 6, 1978 pp 28-37

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.96]

IVANOVA, V. M. and TAGIROV, R. K.

[Text] Using the finite-difference scheme of Godunov, a method, algorithms and programs are elaborated for computer which permit calculation of transonic flow around plane and axisymmetric bodies in channels with perforated walls. Numerical studies are done on flow in wind tunnels with assigned degrees of wall perforation. Numerical and experimental studies were done on the effect that a base support stand has on longitudinal flow around a cylinder having an annular base projection when the channel wall is perforated. Figures 5; references 15.

USSR

UDC 629.78.015:533.6.015.4

A DELTA WING OF OPTIMUM SHAPE IN A SUPERSONIC FLOW

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA [Scientific Annals of Central Aerohydrodynamics Institute] in Russian Vol 9 No 6, pp 38-47

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.103]

NIKOLAYEV, V. S.

[Text] Inviscid supersonic flow around a thin delta wing at a small angle of attack is examined within theory of bands in linear and second approximations. Position of the center of mass of the wing was considered to coincide with the geometric center of inertia of its volume. Variational problems of minimum drag for known lifting force and of maximum lift-drag ratio were solved, the aspect ratio, wing volume and reserve statistical stability being fixed. In the linear statement, optimum shapes are analytically derived; the Ritz method was employed to solve problems in the second approximation. References 2.

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CALCULATION OF SUPERSONIC FLOW AROUND A BIELLIPTICAL BODY WITH WINGS

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA
[Scientific Annals of Central Aerohydrodynamics Institute] in Russian Vol 9
No 6, 1978 pp 48-55

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.106]

GALINSKIY, V. P. and TIMOSHENKO, V. I.

[Text] A numerical method is presented for calculation of supersonic flow of an inviscid thermally nonconductive gas around a three-dimensional body of the aircraft type with a delta wing which has blunted leading edges. Results of calculations corresponding to Mach 6 and angles of attack 0° and 10° are presented. Figures 7; references 13.

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AXISYMMETRIC SUPERSONIC GAS FLOW AROUND A PAIR OF BODIES

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA
[Scientific Annals of Central Aerohydrodynamics Institute] in Russian Vol 9
No 6, 1978 pp 108-114

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.94]

KHLEBNIKOV, V. S.

[Text] By measuring the pressure and thermal flux on the surface of the trailing body, an experimental study was made of the currents formed in supersonic axisymmetric flow around a pair of isolated bodies one behind the other. Results of the study are presented in the form of correlations for pressure and thermal flux as a function of the dimensions of the leading and trailing bodies, their shape, the distance between them and Mach and Reynolds' numbers. Figures 7; references 4.

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STUDY OF THE EFFECT OF A MODEL ON CHARACTERISTICS OF HYPERSONIC DIFFUSERS
AT SMALL REYNOLDS' NUMBERS

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA
[Scientific Annals of Central Aerohydrodynamics Institute] in Russian Vol 9
No 6, 1978 pp 127-132

[From REFERATIVNYY ZHURNAL RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.128]

FILATOV, A. P.

[Text] Results are cited of a study in a vacuum wind tunnel at $M_{\max} \approx 5-13$ of the recovery efficiency of pressure in a system consisting of an underexpanded nozzle and optimum cylindrical diffuser in the presence of a model--a sphere with a diameter corresponding to a load factor of the cross section of the diffuser of $F_m \approx 0.01-0.07$. It was found that when the effective Reynolds' number is changed from about 170 to about 800, the coefficient of efficiency of diffusers η (with respect to pressure recovery in the normal shock wave) increases from $\eta \approx 0.25$ to $\eta \approx 0.55$ when the diffuser section load of the model is $F_M \approx 0.04$. A comparison is made of the coefficient of efficiency of optimum diffusers with that of pressure recovery in shock waves of a free jet without diffuser in identical models. Figures 6; references 3.

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Mechanics of Solids

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THIN-WALLED ELASTIC RODS WITH FIXED AXIS OF ROTATION

Moscow TEMATICHESKIY SBORNIK NAUCHNYKH TRUDOV. MOSKOVSKIY AVIATSIONNIY INSTITUT [Thematic Collection of Scientific Papers. Moscow Aviation Institute] in Russian No 467, 1978 pp 5-9

[From REFERATIVNIY ZHURNAL RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.170 by T. A. Ye.]

DUDCHENKO, A. A., YELPAT'YEVSKIY, A. N. and LUR'YE, S. A.

[Text] Thin-walled rods are often used as reinforcing elements of panels. In this case, when there is deformation together with the construction, the rods twist around some fixed center of rotation lying in the plane of the outer casing. It can not coincide with the center of rotation, relative to which the rod twists in free deformation. Thus in the given case the work of the rods should be characterized by rigidity to torsion which, as calculations show, in some cases may be substantially different from the quantity:

$$GI_a \cdot I_a = \frac{a}{3} \sum l_i \delta_i^3,$$

where a is an empirical coefficient; l_i is the width of the rod flanges; and δ_i is the thickness of rod flanges. Determination of the true center of rotation is only possible on the basis of theory of thin-walled rods which considers shear deformation. In this study is presented theory of thin-walled rods allowing for shear in the median surface. This refined theory permits derivation of relationship of rigidity to torsion of a thin-walled rod with a fixed center of rotation. Reference 1.

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MODEL OF AN ANISOTROPIC NON-UNIFORM PLATE CONSISTING OF FINITE ELEMENTS

Ramenskoye UCHENYYE ZAPISKI TSENTRAL'NOGO AEROGIDRODINAMICHESKOGO INSTITUTA
[Scientific Annals of Central Aerohydrodynamics Institute] in Russian Vol 9
No 6, 1978 pp 93-102

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.166]

POLYUDOV, M. V.

[Text] An elastic mass model of a thin orthotropic plate based on a rectangular finite element is presented. The plane stressed state and flexible deformations of a non-uniform plate are investigated. Coefficients of matrices of generalized rigidities and masses of the element are written in closed form permitting arbitrariness in selecting the basis polynomials for approximation of migrations, stress and intrinsic frequencies of flexural oscillations of a cantilever triangular plate using a rectangular matched element; comparisons are made with the results of other studies. Figures 3; tables 5; references 9.

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STUDY OF VIBRATION-ABSORBING PROPERTIES OF PLATES DAMPED BY RIGID POLYMER COATINGS AND BARS WITH SOFT COATINGS

Kuybyshev VIBRATSIONNAYA PROCHNOST' I NADEZHNOST' DVIGATELEY I SISTEM
LETATEL'NYKH APPARATOV [Vibration Strength and Reliability of Flightcraft
Engines and Systems] in Russian No 5, 1978 pp 47-54

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.167
by T. A. Ye.]

CHERNYSHEV, V. M.

[Text] Dynamic strain of thin-sheet metal constructions subjected to intense vibrational and impact loads may be substantially reduced by using damping coatings made of plastics or special vibration-absorbing materials. Since the effect of coatings is chiefly determined by the degree induced energy dissipation or an increase in dissipation of oscillatory energy, the problem of determining vibration-absorption properties of systems with damping coatings is solved. Plates with rigid polymer coatings and rods

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damped by a layer of soft materials having high vibration-absorbing properties and a rigid, extended, but extremely flexible (compared to the damped rod) constraining band attached to it are investigated. The problems are solved by the energy method. References 9.

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Testing and Materials

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ASSEMBLY AND TESTING OF HYDRAULIC AND PNEUMATIC SYSTEMS OF AIRCRAFT

Moscow MONTAZH I ISPYTANIYE GIDRAVLICHESKIKH I PNEVMATICHESKIKH SISTEM
LETATEL'NYKH APPARATOV in Russian, 2nd edition, revised and supplemented,
Izd. Mashinostroyeniye 1979 256 pp

[From REFERATIVNYY ZHURNAL, RAKETOSTROYENIYE No 5, 1979 Abstract No 5.41.151
by T. A. Ye.]

SAPOZHNIKOV, V. M.

[Text] Operating conditions of hydraulic, fuel and pneumatic systems are examined. Theoretical calculations of permissible assembly stresses, methods of strength calculations of pipelines and their connections are cited. Particular attention is given to questions of assuring system cleanliness, methods of hermetically monitoring, functional tests. In the first chapter are presented operating conditions of hydraulic, fuel and pneumatic connecting lines and results of research are given for loads acting upon system elements during operation. Here too is given an analysis of defects and breakdowns of hydraulic, fuel and pneumatic systems encountered during operation. It was found that many operating defects and breakdowns are due to poor quality of assembly and non-objective monitoring of on-board connecting lines. In the second chapter are cited recommendations for planning tubing, for installing pipelines, arranging fastening elements; methods are given for strength calculations and some methods of reinforcing pipelines and connectors. In the third chapter are examined theoretical foundations and experimental research on strain-deformed state of pipelines and their connections made of various materials: high-strength steels and titanium alloys. Results of a study of loads acting on pipeline connections within elastic and elastoplastic deformation limits and their effect on fatigue strength of detachable and permanent pipeline connections, are given. The fourth chapter contains information on improving technology of assembly and monitoring of connecting pipelines, technological fitting to ensure high strength of assembly and work with least stresses. In later chapters of the book (5-10) are considered questions of technology of washing and servicing hydraulic systems, washing fuels systems and tanks, monitoring cleanliness of working fluids, testing systems for hermetic seal, tests and monitoring of function and safety techniques.

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